BRITISH WELDING JOURNAL

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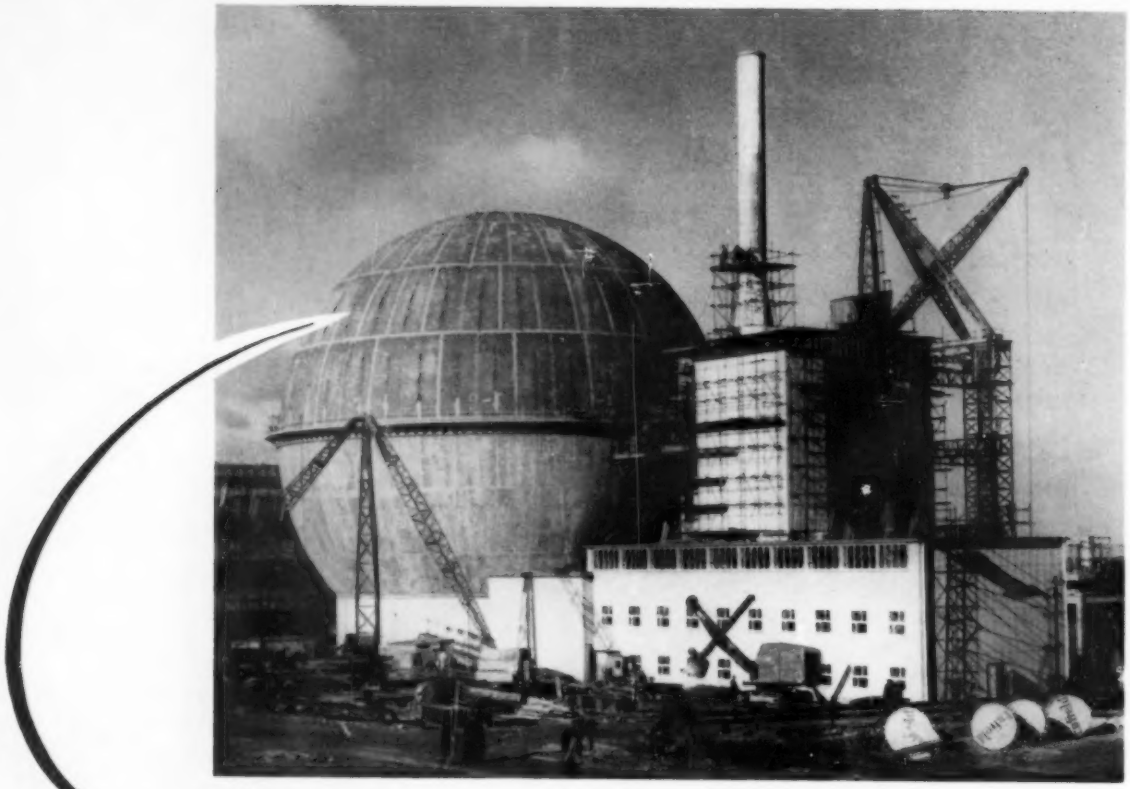

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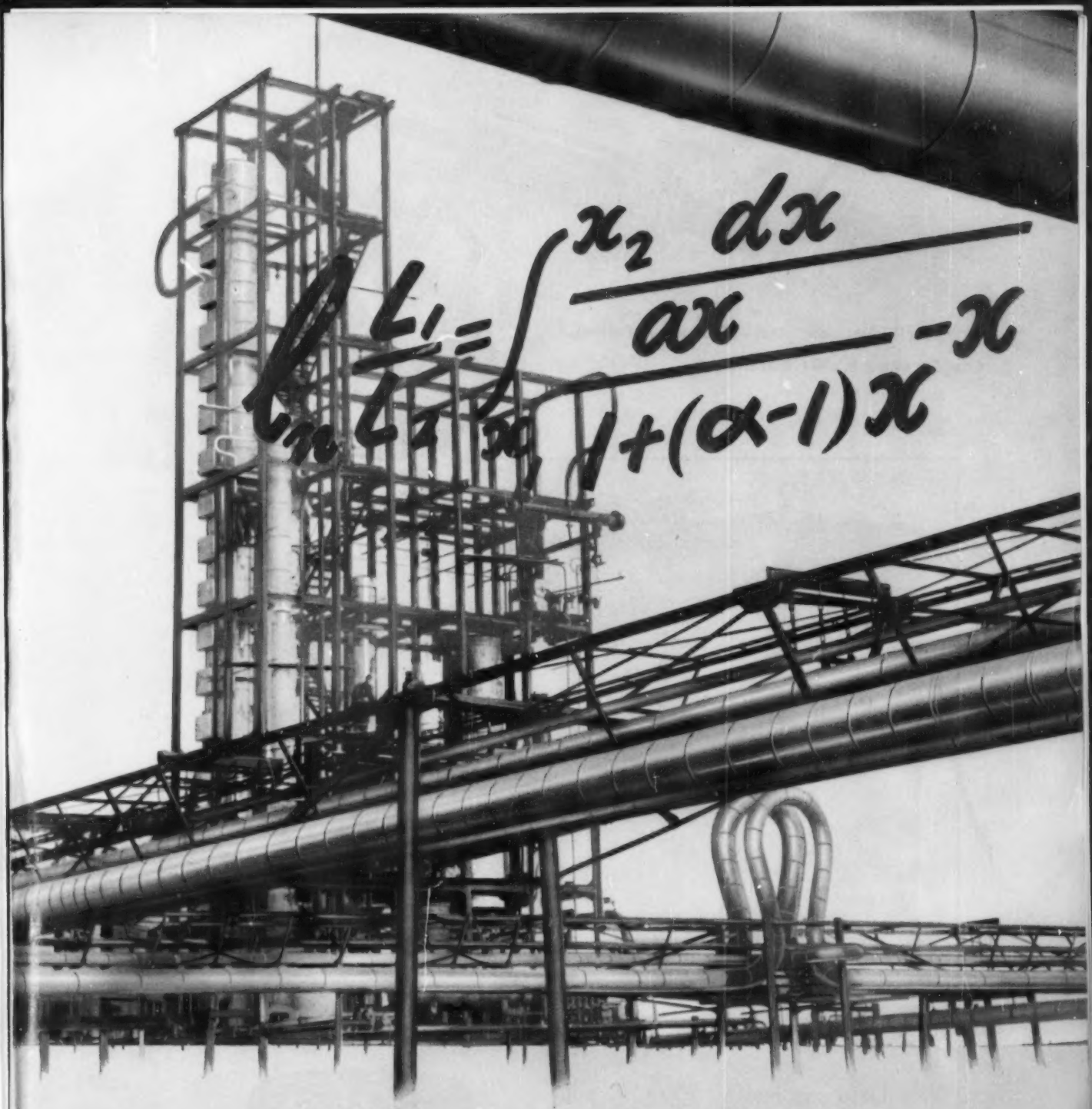

Just as this complex distillation plant may be based on the fundamental Rayleigh equation so too, each component part derives its shape, size, material and method of construction from other scientific criteria. In welding, particularly in the case of alloy steels, the choice of electrode can be critical to the life of the plant

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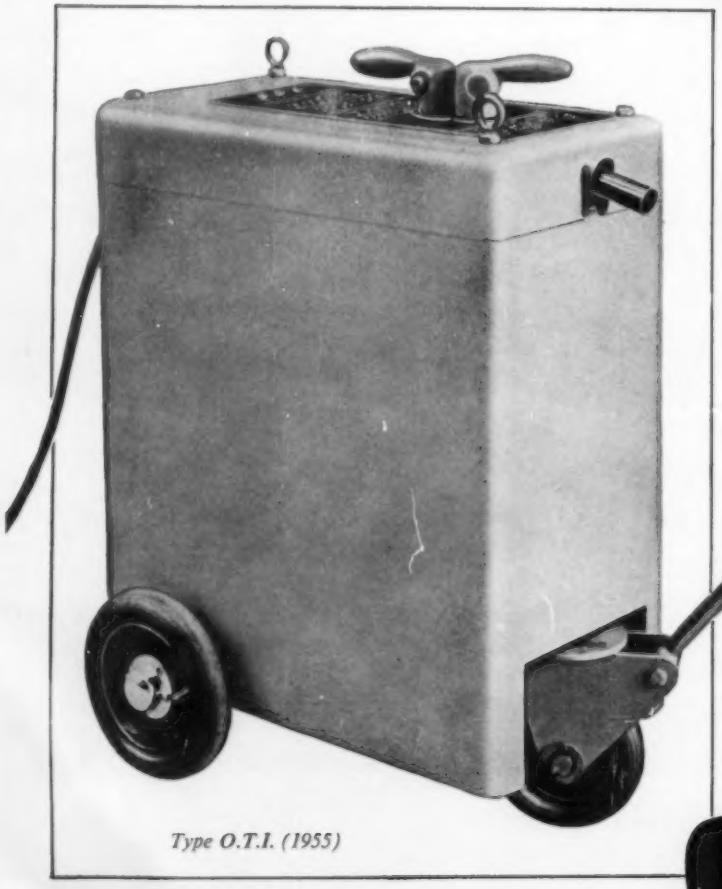

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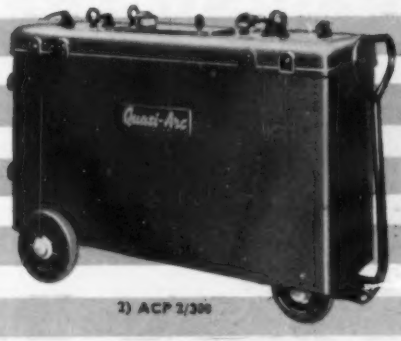

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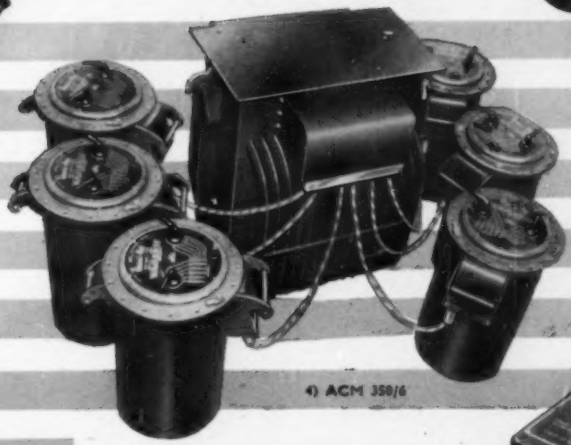

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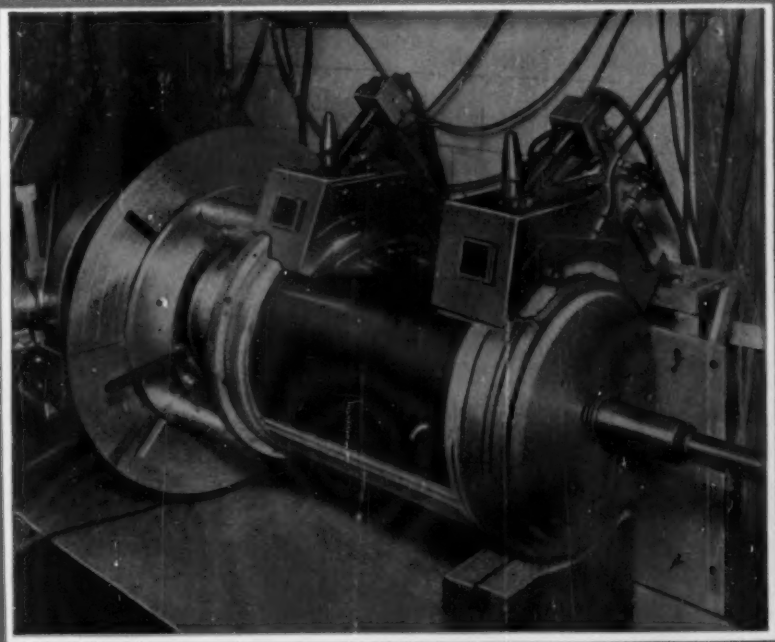

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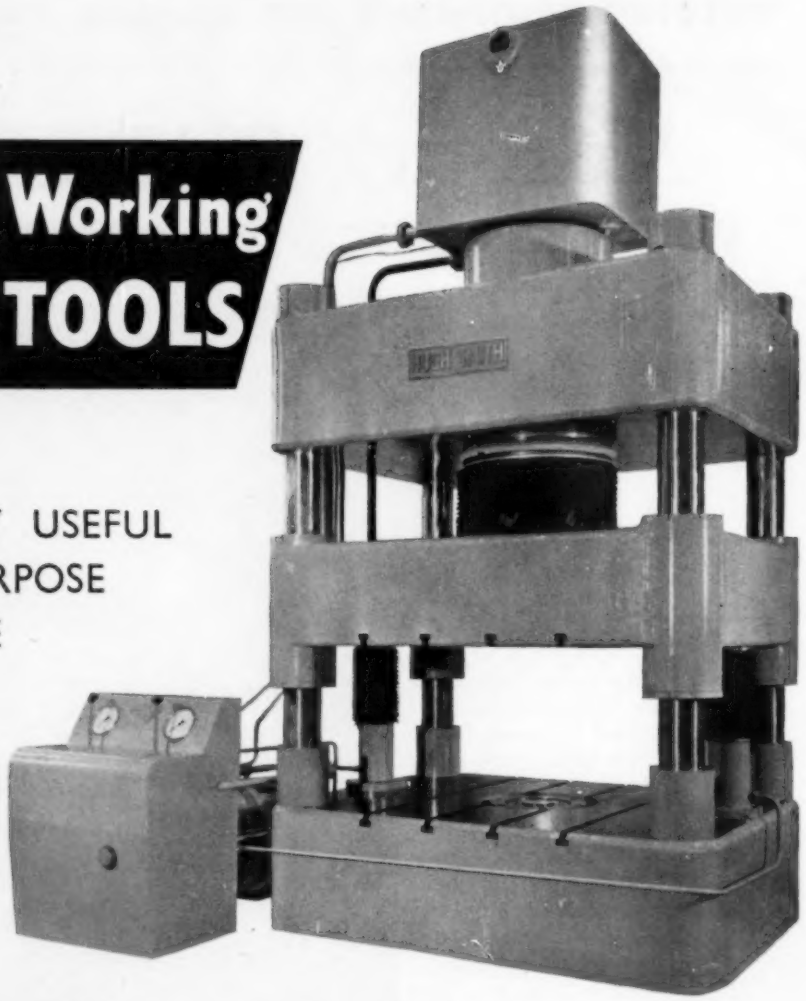

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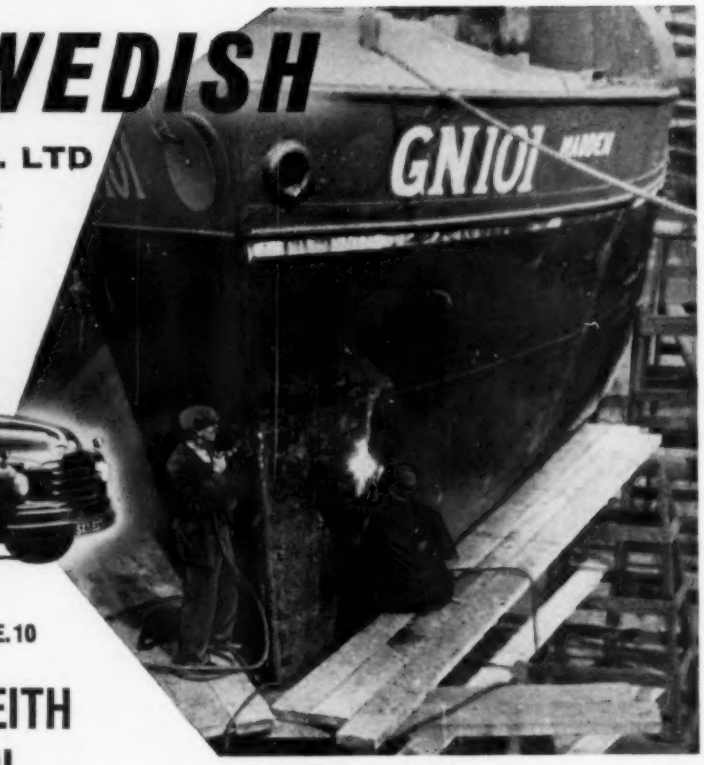

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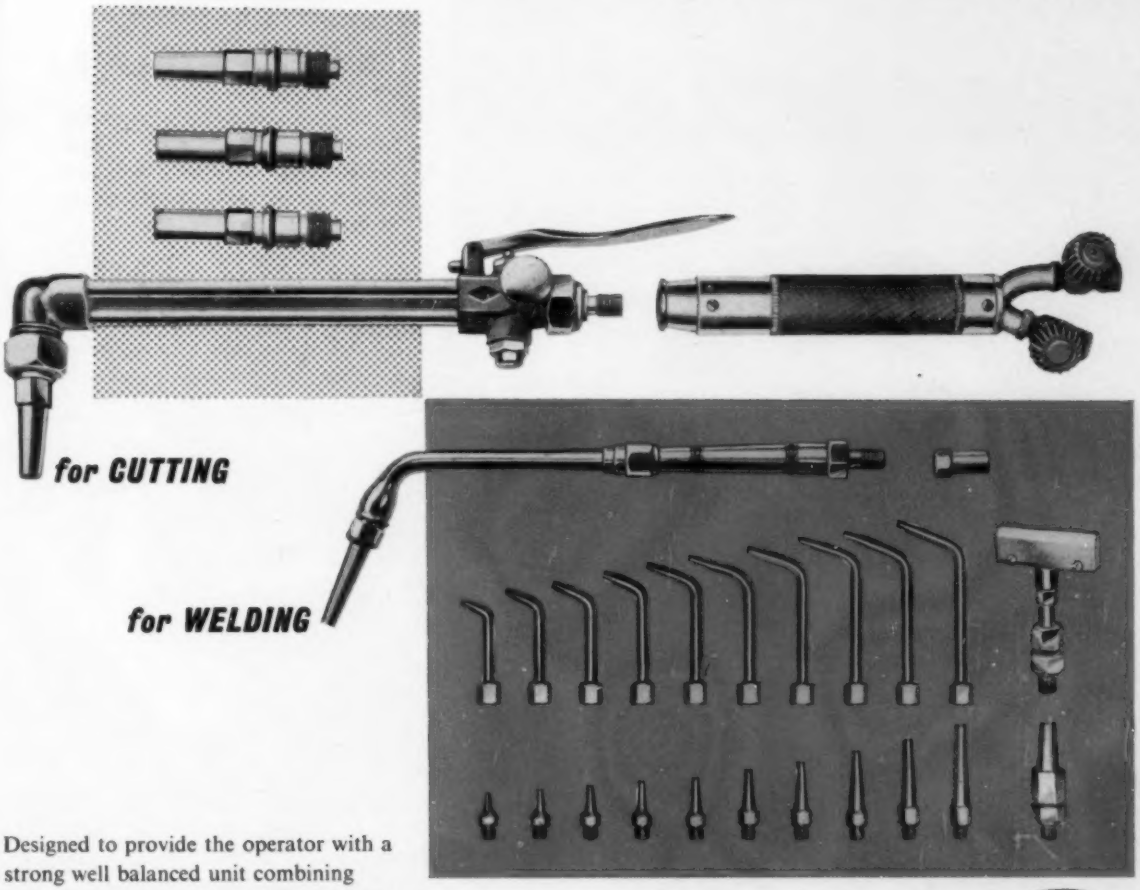

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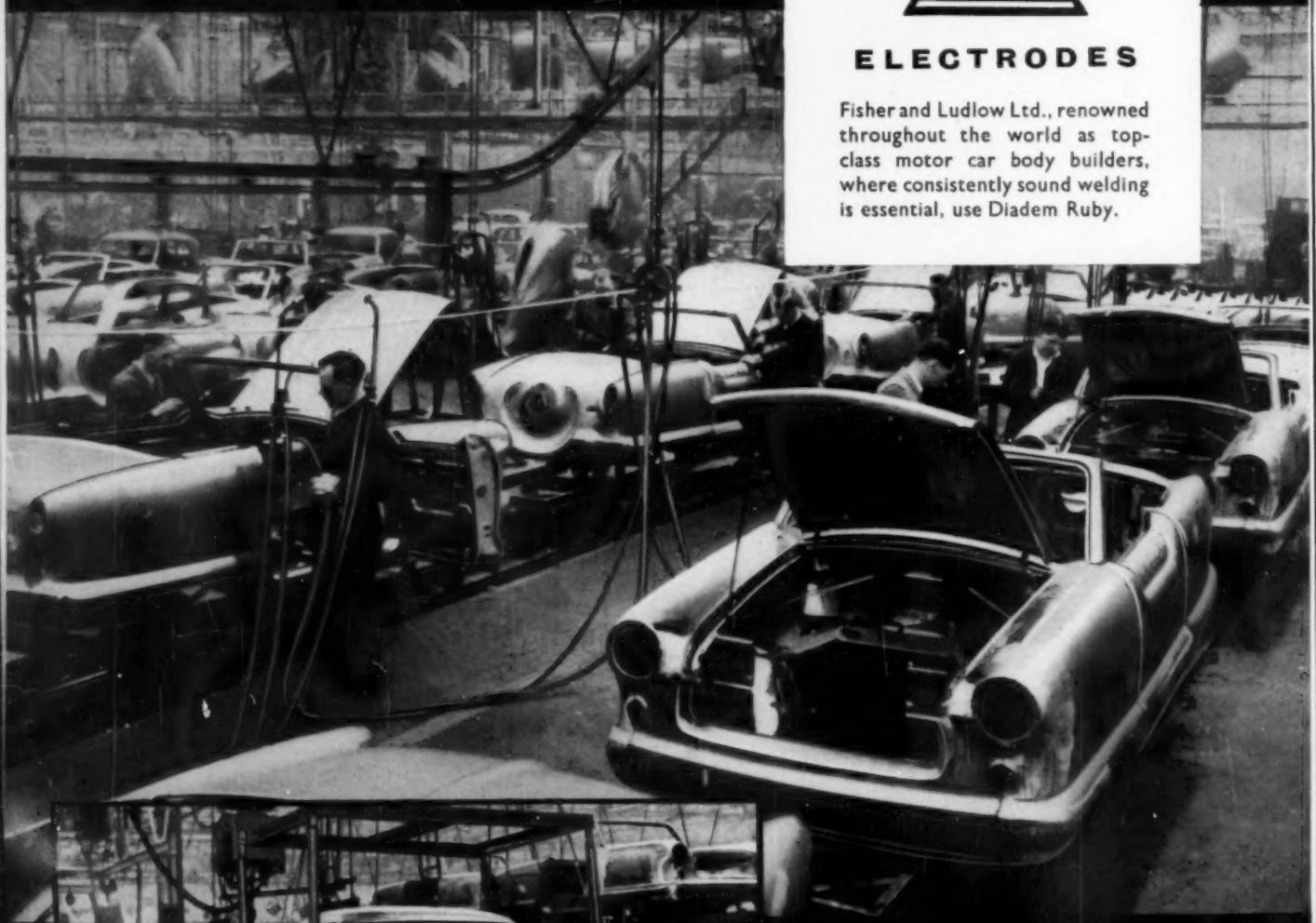

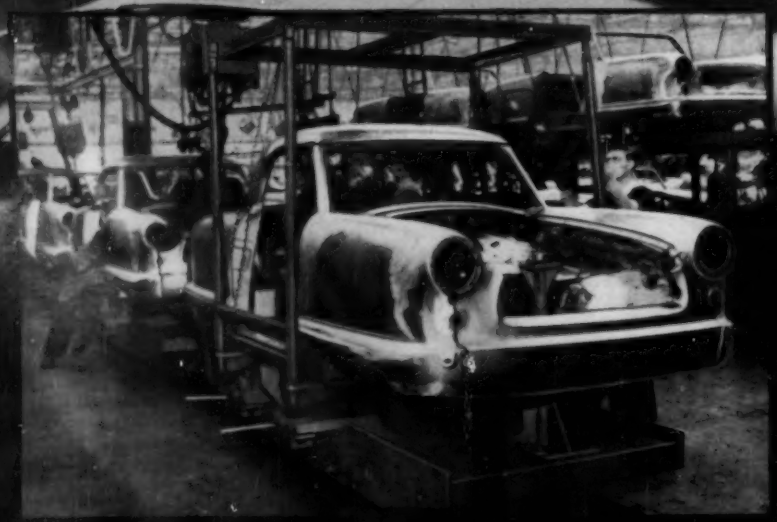

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BRITISH WELDING JOURNAL

Volume 5 JANUARY 1958 Number 1

Editorial

LOOKING FORWARD

The publication by the *Financial Times* last October of a two-page survey of Welding in British Industry is clear recognition of "Welding's Vital Role in New Industrial Achievements", to quote the title of the contribution by Dr. Weck. Twenty years ago comparatively few men clearly visualized the great possibilities of the welding processes. Most of them, no doubt, were among the 908 members of the Institute of Welding, then recently reconstructed to carry through the research programme drawn up at the previous year's Welding Symposium.

The names of the 29 companies and firms which then belonged to the Institute deserve to be remembered wherever welding is used today – and that means practically everywhere in British engineering. Their support, when only men of foresight could see what might come, helped the Institute to nurse the rather sickly infant of welding research, and ten years later to set it on its own feet, as the British Welding Research Association.

"Welding in British Industry" was the title of the *Financial Times* survey. It is exact. One hears men speak of "the welding industry", and one wonders whether they mean the industry which manufactures the plant and supplies for welding, or the industries which employ welding in construction and repair. Usually they mean both, and use the term to cover the all but universal use of the welding processes in the engineering and allied industries. As Dr. Weck said in the article already cited, "There is scarcely any industry today which does not either use welding extensively as one of its major fabrication processes or which ... is not at least dependent on the safe and reliable performance of equipment fabricated by welding for the processes it employs."

Foresight is a rare gift. Ten years ago, after the Institute had successfully completed the task of launching the Research Association, there were many who could see no future for the Institute. That no longer matters, though for some years such doubts made steering unnecessarily difficult. Yet in spite of an appearance of lost momentum, and in spite of what sometimes looked like a wavering course, the position in which the Institute now stands is proof of the distance travelled in the past ten years. There are solid achievements along the track behind – the founding of this *Journal*, the "Handbook for Welding Design", the Education Conference, the British Commonwealth Conference, a permanent home. The forward path is sign-posted by the establishment of a corporate membership which stands for definite standards of scientific and technical competence, and the Institute's development as a teaching body, with its own School of Welding Technology in action all through the year.

When the Institute's function is seen to be education, all its activities fall into place – its meetings and conferences, its publications, its library and information services, its instruction courses, and its membership policy. And their place is alongside the activities of the B.W.R.A., in the promotion of knowledge, and the provision of services complementary or co-operative for the benefit of the engineering and allied industries, of all those who use welding and the processes allied to it, or rely on products that result from their use.

Together, the Association and the Institute can meet the two vital needs for future achievement, to win new knowledge and to convey it effectively to the men who can use it in industry.

Welding

TECHNOLOGY

The South Stand at Cardiff Arms Park

By J. M. Burke, M.A., A.M.I.Struct.E.

SYNOPSIS

ANY grandstand sets a special problem for the structural engineer, but site conditions greatly influenced the shape finally chosen for the Arms Park stand.

After a discussion of the planning of the job, the text continues with a description of the detailed design and construction, with particular reference to the steelwork.

Speedy erection of steelwork, roofing, and precast concrete terracing contributed to the completion of the stand on time, despite the fact that access could be gained from the ends only.

ANY grandstand which is required to seat a considerable number of people must be particularly interesting to the structural engineer. The peculiar asymmetry of structure entails problems in planning and in detailed treatment which place such a project in a class by itself. Moreover, the finished building will have a bare appearance and the structure will be exposed in a manner which one normally associates with industrial buildings; but the grandstand will attract the attention of a greater number of people, and will in effect be a most important public building. Its good appearance will be largely dependent on the form and detailing of the structure, which in turn depend upon the correct expression of structural function. The structural engineer will therefore find in such a project a unique opportunity to marry the technology of modern structural materials with an unusually stringent specification.

This project, therefore, was considered as a special structure from the earliest stages, although its final form was largely influenced by the necessity of designing for existing site conditions. The Arms Park ground (*see* Fig. 1) is an area enclosed on all four sides by fixed boundaries. Within the ground, the annular area devoted to accommodation for spectators was already mostly occupied by grandstands, open terraces, and enclosures. The provision of the required *additional* seating was only practicable in one area, on the South side. Behind the enclosed South Stand was a cinder roadway, 40 ft wide for most of its length, which connected the two main entrances on this side of the ground and gave access to the stand. This 'dead' space could obviously be used to greater profit, and a structure could be arranged in it which would provide the maximum number of additional seats, retain the existing circulation arrangements, and offer a viewpoint far superior to that given by the only alternative positions, the East and West ends.

If the existing small South Stand were demolished, any type of grandstand could in theory be built on this site—two-tier, single-deck, or some halfway compromise. However, a very tall structure on the South side would cast a perpetual shadow over the whole field during the playing season, and since the field is very low-lying, this would greatly increase the difficulty of keeping the pitch in good order. The point was important in fixing both the height of the roof and its forward projection, and it was agreed that the design would be a single-deck. There was thus no need at present to demolish the existing stand; the new stand was to be treated as a rearward extension, although provision was made in the design for the future rebuilding of the existing stand.

The final terms of reference for the design could be summarized as follows:

(1) A structure to carry the maximum number of covered seats was to be erected behind the existing stand, the roof only of the latter to be dismantled
(2) Provision was to be made to facilitate future rebuilding of the existing stand, and for extensions, if required
(3) The shadow cast by the new roof was to be kept to a minimum
(4) The existing roadway was to be retained under the new structure
(5) A new camera room and judges' box for the Greyhound Racing Company was to be provided to replace the one on the old roof, and additional lavatories were to be built.

Strict cost control was required to a budget figure, and time was of great importance since only ten months were available for design and construction, from April 1955 to February 4th, 1956, when the stand

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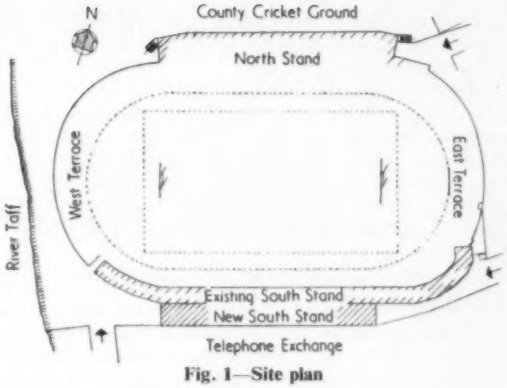

Fig. 1—Site plan

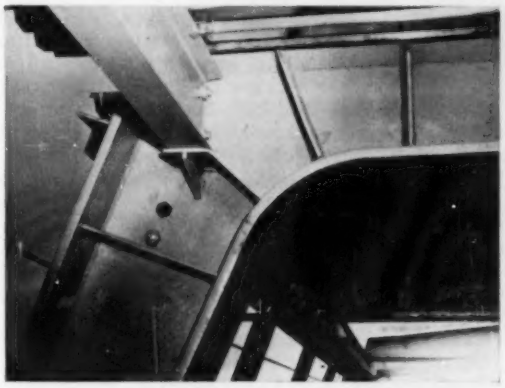

Fig. 3—Roof-girder knee

was to be opened for the first international match of the season. Further, the existing arrangements at the stadium were not to be disrupted by the construction, since the job could not be completed in the summer or non-playing season, and in any case greyhound racing continued throughout the year.

GENERAL ARRANGEMENT

The overall dimensions of the stand, and the general arrangement, were fixed by the conditions described. In view of the time factor and the constricted site (there would be no room at the back or front for access to the construction), it was decided to keep the length of the stand down to the maximum straight run which could be accommodated, since this would avoid complication. The length is roughly that of the straight sides of the stadium, and provides 337 ft 6 in. clear run of seating.

The depth of the stand, between the back of the existing structure and the site boundary, is about 40 ft, in which sixteen rows of seats are accommodated (*see* Fig. 2). The terraces are spaced 2 ft 3 in. nosing to nosing, and the rake is 1-in-2, which is very near the ideal for the position of the stand.

The primary consideration in laying out such a stand is the safety of the users, particularly in connection with exits, gangways, and barriers. Regulations in these matters vary from place to place, but many stands take far too long to clear. A maximum permissible time limit was fixed, i.e. that the exits should clear a full-capacity crowd (over 3300 people) in ten minutes under normal circumstances. Calculation showed that four staircases would be required, each 8 ft wide, and the theory is borne out in practice by the fact that the stand clears in approximately 8 minutes.

The staircases are arranged in alternate bays, and are designed to leave the roadway clear by employment of the dead space between the rear legs of the

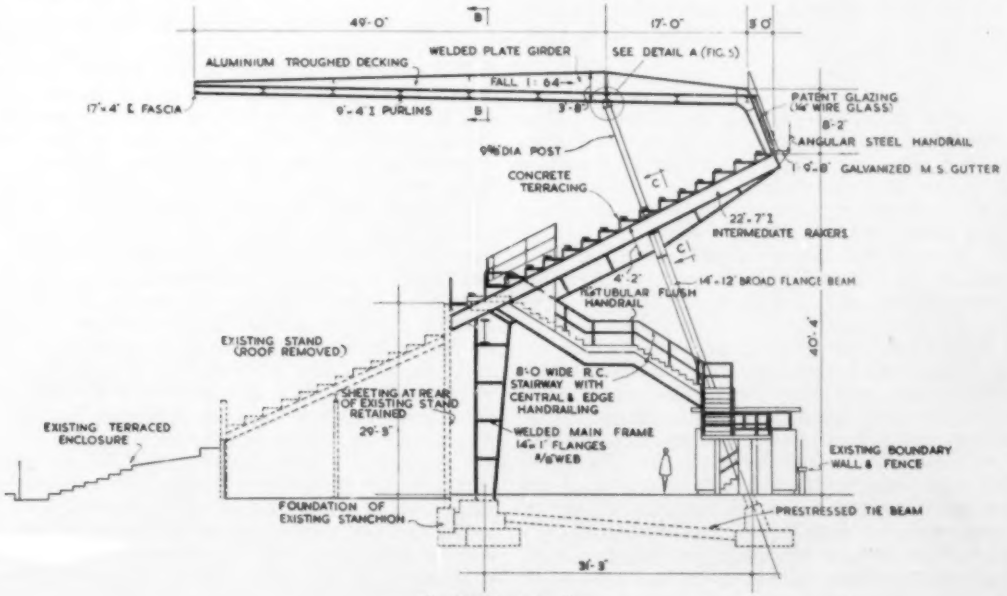

Fig. 2—Cross-section

stand. Each staircase springs from a platform at ground level in two double flights four feet wide. These recombine at a higher level and become a single flight eight feet wide, which flies over the roadway into the stand. In the three odd bays between the staircases, and again between the rear columns, are sited lavatory blocks, built in brickwork with concrete roofs.

The main subframes, and the roof girders over, are spaced at 37 ft 6 in. centres, 9 bays in all. This grid offered reasonable sections for the purlins and roof girders; also it is a multiple of the grid of the existing stand, and thus by staggering the new stanchions between the old (which are at 12 ft 6 in. centres), it was possible for the foundations to be placed without resorting to underpinning, except in one case.

On account of the age and condition of the existing building, the new stand was designed to be structurally independent, and the only alteration made to the former was the demolition of the roof, to clear the view from the new seats. The new roof is therefore arranged to cover both stands, i.e. a depth of 66 ft.

It was decided to use a cantilever design for the roof, which offered many advantages; e.g. it dispensed with the provision of awkward foundations amid the existing structure, and it would not be affected by future development at either end of the stand. Further, it was felt that an unobstructed view for the greatest possible number of spectators should be a feature of any modern stand. This point has until quite recently been discounted in many cases, the row of columns at or near the front of many stands forming an undesirable feature, which was incorporated mainly on economic considerations. Advances in knowledge and treatment of materials, and particularly in improved welding techniques, have now made possible the omission of these obstructions, without a great increase in cost. In the present instance, however, the weight and cost of 66-ft cantilevers were disproportionately heavy, and the tubular props which are provided 17 ft forward of the rear leg show a worthwhile saving, but do not form a serious obstruction.

ROOFING

The roof covering is 20 s.w.g. aluminium-alloy troughed decking, and spans a maximum of 8 ft 4 in. between purlins, to which it is secured by clips (*see* Fig. 3). The fall is in one direction only, towards the rear of the stand, an arrangement which obviates a front-edge gutter with its attendant difficulties. Both to reduce the size of the shadow which would normally be cast on the field, and to obtain the best possible sheltering of the seats, it was realized that the front edge of the roof should be as low as possible. It will be seen from Fig. 2 that, despite the rearward fall, the fascia is not much higher than the lowest level which would give clear sight lines; this has been achieved by dropping the roof between the main cantilevers, at each side of which trimming flashings are provided, and by using only a slight fall (1 in 64). While this outline was under discussion, the elimination of the customary membrane and insulation, and the use of plain exposed aluminium troughing, were considered; such a decking would be very light, durable, and cheap, although no precedent could be found for its use on so flat a pitch. After tests had been carried out, the exposed decking was adopted, and was fully waterproofed by the provision of a 9-in. end lap sealed with self-adhesive strip.

Shelter from the weather for the stand above terracing level is completed by continuous patent glazing along the rear face and by glazed screens at either end. Water draining from the roof is allowed to cascade down the rear glazing to be collected in a large box gutter at the foot which is provided with a handrail and also serves as a maintenance walkway.

DESIGN OF SUPPORTING STRUCTURE

Site conditions, the vast area to be covered, and the great savings which could be made in the substructure and foundations by reducing the weight of the roof, pointed to the adoption of exposed steelwork as the right material for the roof framing.

Steelwork is also used for the substructure, though for slightly different reasons. Although it was felt that concrete might give a better appearance, a precast scheme would have presented considerable difficulties associated with the handling of large and heavy sections in a very restricted space, whilst an *in situ* concrete design would have caused unnecessary disruption of the stadium business and would in addition have been uneconomic.

The roof purlins are discontinuous 9 in. × 4 in. R.S.J.'s spanning the bay lengths of 37 ft 6 in. between the main cantilevers, which are carried on 9⅝-in. outside dia. raking tubular props and anchored to the subframes at the back of the terracing. The anchor and cantilever form a continuous frame, both being **I**-sections comprising 14 in. × 1 in. flange plates welded to a ⅜ in thick web of varying depth, with widely spaced stiffeners; for the outer 20 ft the structure is lightened and its appearance improved by reducing the flanges to ¾-in. thickness, tapered on plan.

Longitudinal wind forces in the roof structure are resisted by horizontal cross-bracing of angle section bolted to the lower flanges of the purlins, three sets being provided across the full width of the centre and end bays. It was not convenient to arrange bracing in the plane of the tubular struts, and so the purlin bracings act as horizontal cantilevers, the fixing line being the rear edge of the roof. The resulting shear is taken into light Vierendeel girders inside the rear glazing in the three braced bays, and the twisting or racking action in the plane of the roof is opposed by bending of the anchor legs and cantilevers. The three braced bays are assumed to act equally, and thus the racking forces are shared between three pairs of roof frames, enabling all the cantilever assemblies to be identical in section, without loss of economy. The bracing in the end bays also eased the work of erection considerably. Below terracing level, only one bay is braced against longitudinal forces.

The main subframes are also at 37 ft 6 in. centres and carry the roof loads directly. Each consists of a half-portal of welded **I**-section, the tapered front leg springing from a pinned base and turned at the top into a raking beam under the terracing. The roof load is imposed on this frame by the mutually opposed actions of the tubular strut and rear anchor leg, and it

will be seen that the centroid of the roof load is so placed that the upper structure is virtually poised on the front stanchion. The frame is propped by a pin-ended strut (14 in. × 12 in. broad flange beam), which provides stability and carries a large proportion of the load from the terracing. The latter is designed to span on to raking beams (22 in. × 7 in. R.S.J.) placed at the third-points of the bays and bearing on the plate web girders which are supported directly on the main stanchions, as shown in Fig. 2.

The broad flange beam strut and the tubular roof strut are arranged in line, for the sake of appearance and economy, the line being determined by the need to support the roof girder reasonably far forward at the top while at ground level the roadway under the stand is left free of obstruction.

All the built-up **I**-sections (i.e. the longitudinal beams, roof girders, and half-portals) were designed to employ the same basic components, namely 14 in. × 1 in. plates for the flanges, and $\frac{3}{8}$-in. thick plate for the webs and stiffeners, for both of which the contractors were able to obtain favourable delivery dates.

The steelwork is protected by two-coat alkyd paint over red lead primer, all of which was applied after erection (except for contact surfaces). The primer is, however, omitted from the purlins, which before delivery were coated with a sprayed film of aluminium 0·004 in. thick.

DETAILED DESIGN

Despite the unusual appearance of the structure, analysis was relatively straightforward, since the frame is statically determinate, although a large number of loading combinations had to be considered owing to the sizeable wind forces.

All loadings were calculated in accordance with the provisions of British Standard Code of Practice 112, Chapter V, which gave a basic pressure of 20 lb/ft² to be used in designing against wind. Particular attention was paid to the air drag which was assumed to act on both upper and lower surfaces of the roof and added 11 tons to the normal longitudinal forces to be resisted by the bracing. Allowance was also made in the rigid bay for the effect of surging of a crowd in its enthusiasm.

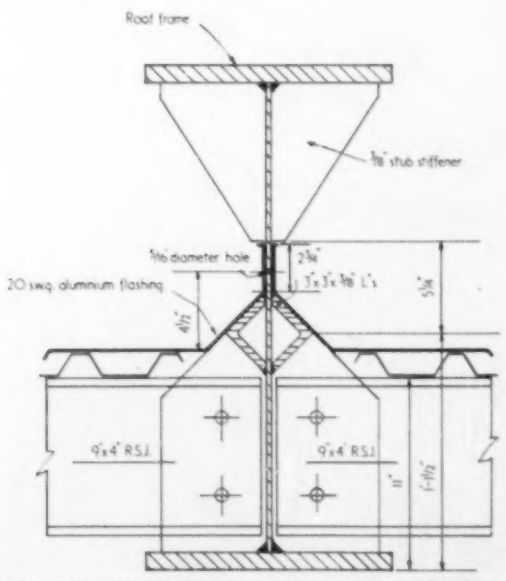

Fig. 4—Aluminium flashing to roof frame (section *BB* in Fig. 2)

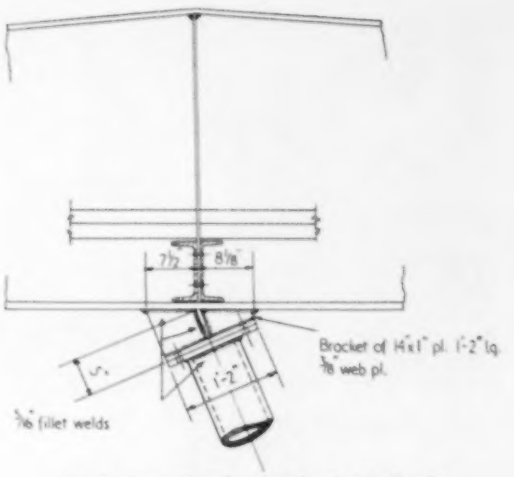

Fig. 5—Apex of roof girder (detail *A* in Fig. 2)

Some of the many features of the structure may be mentioned here which are not apparent to the casual observer, and which show the importance of attention to detail in working out a design.

The design of the roof girders, which cantilever 50 ft from the props, was complicated by their being partly exposed above the decking. A fully waterproof joint between decking and girder web was achieved as shown in Fig. 4; the bearing stiffeners to which the purlins are connected do not interrupt the run of the flashing, being cut off by continuous horizontal angles welded to each side of the web. The only exception occurs at the apex of the girder, where full-depth stiffeners are provided (Fig. 5). It will be readily appreciated that, in such a light roof structure, reversal of the cantilever action can occur under the action of wind forces, and some restraint must be provided against lateral buckling of the upper flange. In the present case the apex of the girder is the only critical point, and sufficient restraint is provided by the use of a stiffer purlin (two 9 in. × 3½ in. channels stitch-bolted back to back) which is connected to the heavy girder stiffener by turned and fitted bolts.

The reversal of stress also required the use of high-tensile bolts in the connections at head and foot of the tubular prop. These connections provide for the cap plates of the strut to be square to its axis, and also avoid drilling of the main flanges of the frame—saving double handling in the shop and loss of effective section in design (*see* Fig. 6).

It was felt that the possibility of abnormal pressures building up inside the natural funnel profile of the stand should not be overlooked. Such conditions would occur only with exceptionally severe squalls, but since time was not available to conduct wind-tunnel

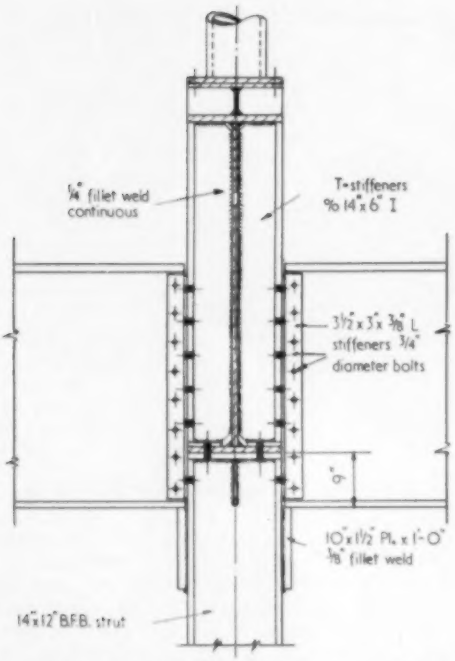
¼" fillet weld continuous
T-stiffeners to 14"x6" I
3½"x3"x 3/8" L stiffeners ¾" diameter bolts
10"x1½" Pl. x 1'-0" ⅜" fillet weld
14"x12" B.F.B. strut

Fig. 6—Connection of struts to main frame (section *CC* in Fig. 2)

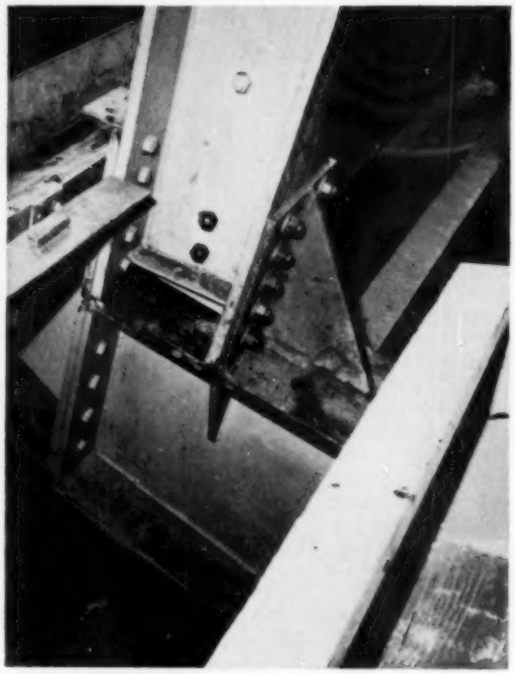

Fig. 7—Base of roof anchor leg

tests which would give accurate information, it was decided to incorporate in the rear glazing four large top-hung lights which would open outwards under a pressure of 15 lb/ft².

The last main site connection of the roof girder occurs at the base of the anchor leg, and is shown in Figs. 7 and 8. This was designed using site bolts in shear, which were fitted in holes reamered to exact size on site, thus ensuring correct levelling of the roof. The outer (loose) cover plate also carries the gutter bracket, a ⅜-in. thick triangular plate welded on.

Similar brackets are fixed to the ends of the intermediate cantilevered terracing beams, and a pair of angles bolted to the brackets support the gutter throughout its length. The gutter itself is formed of ¼-in. mild-steel plate pressed to shape in sections, which were then butt-welded into 37 ft 6 in. lengths. After the butt straps and other fittings had been welded on, the complete assemblies were galvanized before delivery to site.

The principle of avoiding drilling of the flanges of main members was adhered to in designing connections throughout the structure, but an exception was made in the detail at the head of the lower rear strut. Here it was necessary to secure the main beam by two holding-down bolts, and covers were welded to the flange accordingly (Fig. 6). Figure 6 also shows how the longitudinal girders bear on slab seatings, giving minimum eccentricity of loading and a neat appearance.

DESIGN AND CONSTRUCTION OF FOUNDATIONS

The design of the foundations had been based on the results of three bores, and a shallow pit which had been dug to prove the foundations of the existing stand. The bores showed not more than five feet of fill

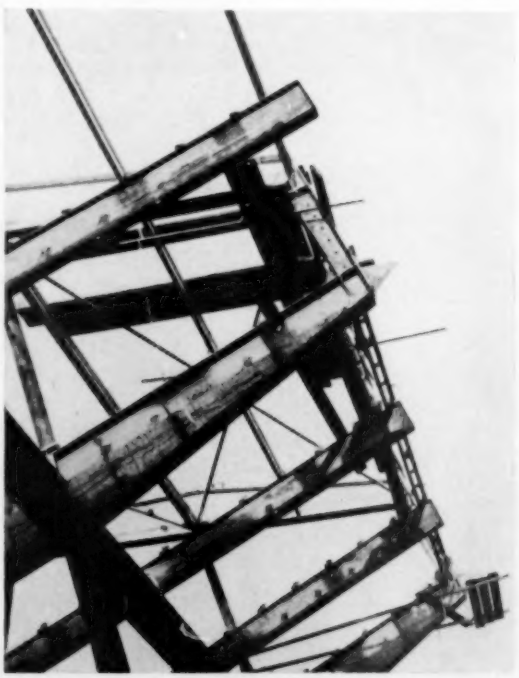

Fig. 8—View of first bay from below

overlaying alluvial deposits of sandy clay, capable of carrying about 1·25 tons/ft²; also, water was indicated at about 7 ft–7 ft 6 in., and the excavations should be kept above this level if possible. Some anxiety was caused by the knowledge that a considerable depth of fill had been found on the adjacent site of the Telephone Exchange, and in other positions nearby, but reassurance came from reference to an old plan of Cardiff, which showed that the old river bed ran roughly from West to East in a channel a little to the South of the site. The Exchange was therefore almost directly over the old deep channel, whereas the new Stand would be over its North bank.

Spread concrete foundations were adopted and designed for a ground pressure of 1·25 tons/ft² at a depth of 6 to 7 ft: owing to the heavy loads on the front basis (130 tons at full load) these were designed in a **T**-shape to clear the existing foundation blocks. The design of the steel subframe causes horizontal thrusts of 27 tons similar to a portal effect, which are resisted by precast prestressed concrete ties. The ties were cast at works in a stressing bed, transported to site, and dropped into the prepared trenches. This design saved a great deal of time on site, and since the process of excavating the trench, placing the tie, and backfilling occupied only a few hours, the road access was not seriously interrupted. The ties are 34 ft long and, weighing just over a ton, were easily handled by a small mobile crane.

The half-portal is designed as a hinged-base frame, but owing to the great stiffness of the frame, it was not thought necessary to take any special precaution against the transmission of moments by the tapered leg. The horizontal thrust, however, has to be carried into the foundation, and this was arranged by welding a heel plate on to the baseplate, which bears against a concrete upstand. Otherwise the baseplate is a plain slab with two small bolts (*see* Fig. 9).

Fig. 9—Half-portal base

Fig. 10—Two subframes erected (26th September, 1955)

Since the point of application of the thrust and the tie beam are at different levels, the centroid of the base is placed forward of the centre line of the stanchion, to provide an opposing moment.

The foundation contract also included the subsidiary foundations and drainage for the staircases and lavatory blocks, and was completed at the end of August, 1955.

FABRICATION AND ERECTION OF STEELWORK

Meanwhile fabrication of the steelwork was pushed forward. The main frames are of exceptional interest, and are a fine example of careful plating and assembly work.

Provision was made on the drawings for one site-welded butt joint in each **L**-shaped subframe, and although eventually this joint was made in the shop and the frames were transported to site in one piece, it was found convenient to assemble the main components in advance of this operation.

The flanges and web of each section were first formed into an **I**-section, the ¼-in. continuous fillets being laid downhand with the web vertical by two operators working from both sides simultaneously. After machining of the stanchion bearing and fitting of the baseplate, the two sections were laid out flat, lined, and levelled ready for butt-jointing. It was deemed preferable to carry any contraction stresses in compression in the flanges, rather than in tension, so the flange butt welds were completed in the vertical position, and the web weld was then made downhand using low-hydrogen electrodes to minimize the possibility of cracking. Finally, stiffeners were fitted and minor components added.

A similar sequence of operations was observed in assembling the roof girders, which were each made up in leg, centre, and front sections. In order to ensure good fit on site at the rear anchor point, each roof leg was fitted to the appropriate frame and drilled before joining to the centre section.

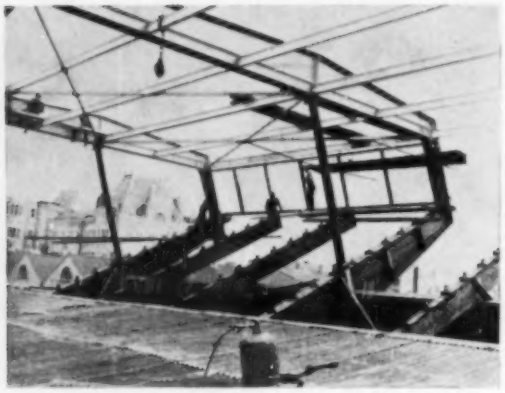

Fig. 11—First bay almost complete

Fig. 12—8 Bays almost complete (end of November, 1955)

The entire job includes approximately 25,000 ft of ¼-in. fillet weld and about half of this footage—notably the main fillets of the frames—was laid with twin-arc equipment. The process uses a large heat input and a high rate of travel for small welds, which resulted in speedy work in the shop. The fabricators attained a consistently high standard of workmanship, the welding in particular presents an exceptionally neat appearance, and the adoption of a proper welding sequence led to the completed members being free from distortion.

Special precautions were taken in welding end plates to the tubes, since the material was a steel containing 0·4% of carbon and much manganese, the only material available for this section. The tubes were preheated and welded with low-hydrogen electrodes.

The care taken with the fabrication of the first main frame delayed its arrival at the site until the third week in September, 1955. This loss of time paid a dividend, however, since thereafter the frames were produced without major incident at the rate of one a week complete, together with the corresponding longitudinal girders and R.S. sections.

The erection was carried out using a Scotch derrick fitted with a 120-ft jib, and was worked from the East end and through towards the river. Throughout, difficulty was caused by the lack of stocking space; the minor members and one or two roof frames could

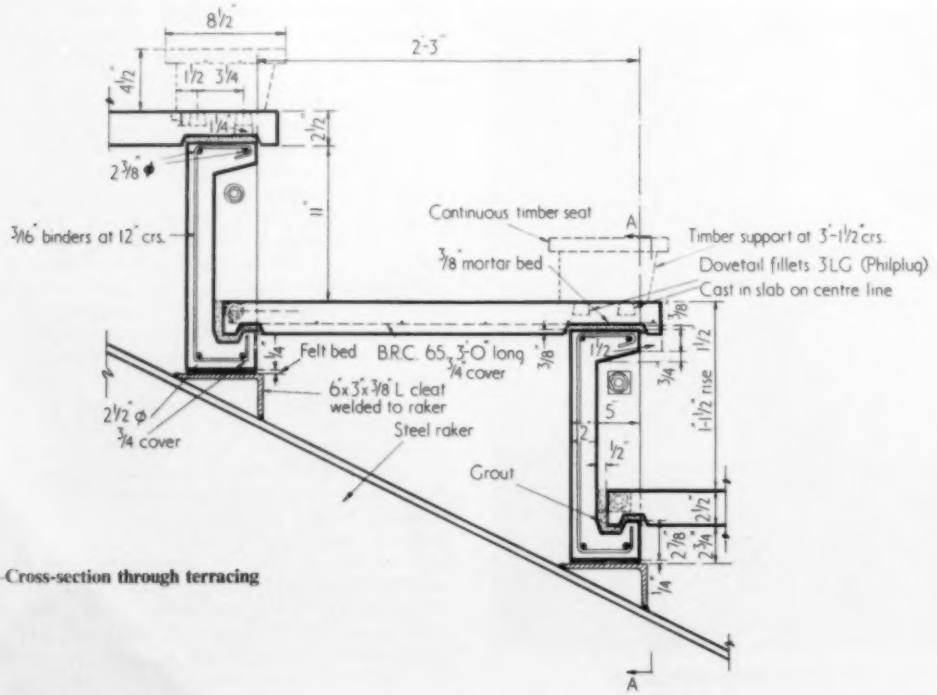

Fig. 13—Cross-section through terracing

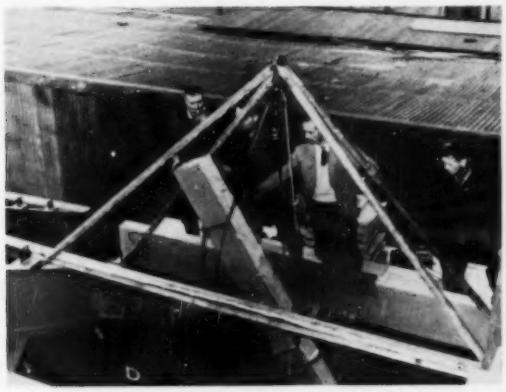

Fig. 14—Erection of terracing

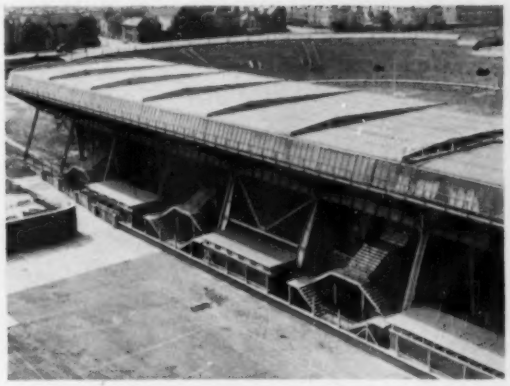

Fig. 16—Rear view of completed stand

be kept on site at one time, but the main frames had to be erected as soon as they arrived (*see* Figs. 10–12).

The first pair of subframes were readily boxed in with the longitudinal girders, and the corresponding roof frames were lifted into position and guyed until the bracing in the first bay of roof was complete. The erectors used a temporary stanchion seated on the most forward point of the subframe to facilitate fixing of the roof frame, and this is to be seen in the progress photographs.

It was necessary to complete each bay before moving on to the next in order to make the best use of the crane, and the erection proceeded at the rate of one bay per week complete, with all members and bolts in place. After erection of the centre rigid bay at the beginning of November, 1955, the first half of the stand was lined, levelled, and grouted to release operations on the painting, roofing, and terracing, while work on the framing continued.

TERRACING

It had been resolved that the terracing should be incombustible and precast concrete was the material chosen, the seating only to be of timber. The design had been worked out in time for production of the units to begin early in September, 1955. The scheme consists of slabs 18¾ in. long and 2½ in. thick (which are light enough to be handled by one or two men), supported on channel section beams spanning 12 ft 6 in. between rakers. Each pair of beams in line is bolted together by two bolts passing through the end ribs. The lower bolt also picks up a vertical location plate which is welded to the flat surface of the bearing; the latter is formed by a 6 in. × 3 in. R.S. angle cutting, which in turn is welded to the raker.

Fig. 15—Seven bays of terracing complete (mid-December, 1955)

The profile of the beam (Fig. 13) shows the raked edge of the top flange (for easy stripping from the mould), and the recess to receive the slabs which are bedded in mortar. The design includes felt packings at the bearings and end-ribs for levelling and manufacturer's tolerance.

The units were transported from works by semi-trailer unit in groups of beams and slabs as required, and lifted direct from the trailer into position by means of an electric hoist on the ground. A special four-post headframe was evolved to clip on to the steelwork and support a single pulley block (*see* Fig. 14).

This system proved very successful on site; it did of course require the continuous employment of (usually) one tractor and three trailers, but it resulted in enormous saving of time and effort, owing to the virtual elimination of double handling on the job. The terracing (about 1500 square yards in area) was completed in under 9 weeks (*see* Fig. 15).

Once the erection of the terracing was under way, the following trades were able to proceed with the construction of minor buildings, staircases, fixing of seat timbers, dismantling of the old roof, suspension of the judges' box and so on.

The stand (Fig. 16) was opened on the appointed date, 4th February 1956, the occasion of the Scottish International match at Cardiff.

ACKNOWLEDGMENTS

The author, on behalf of the consulting engineers, would like to express appreciation of the co-operation which was received from all quarters in connection with this project, and particularly from the contractors engaged on the work. Their enthusiasm and willingness to accept new ideas contributed largely to the successful completion of the stand within the scheduled time, eight months from the opening of the site.

Welding of the Deckhouses of the *Bergensfjord*

By H. D. Archbold

SYNOPSIS

THIS paper gives an account of the work undertaken in the construction of the aluminium deckhouses on the m.v. *Bergensfjord*. It deals with the experimental work connected with aluminium welding under shipyard conditions, the prefabrication and construction of the deckhouses, and gives edge-preparations and welding conditions found to be most efficient.

Introduction

THE construction of the 18,700-ton Norwegian America Line vessel *Bergensfjord* was a landmark in shipbuilding progress, in that 410 tons of welded aluminium plates and sections were used in the construction of the deckhouses. The original design arrangements were prepared on the basis of the *Oslofjord* which had 60 tons of riveted aluminium incorporated into the uppermost tier of deckhouses and funnel. The rapid development in the welding of aluminium encouraged the owners to request that the *Bergensfjord* deckhouses be all welded.

The use of this light alloy has tremendous advantages to both the shipbuilder and the shipowner. Longer houses may be contemplated, giving more passenger accommodation and greater space for public rooms such as dining saloons, lounges, and foyers. From the shipbuilder's point of view aluminium opens up a completely new field of construction, and often a complete change in technique. Prefabrication can be considered on a large scale, individual panels being governed by size rather than weight. Plates and sections of medium size can be moved with ease by the personnel, where the steel equivalents would require the use of a crane.

By comparison with the *Oslofjord*, the bridge front of the *Bergensfjord* is about 50 ft further forward, and some of the decks are extended further aft, thereby providing accommodation for 67 more passengers in the deckhouses and enlarging the space available for public rooms on the promenade deck.

The owners stipulated that the aluminium was to be supplied by a Norwegian company, who manufactured larger plates than were available in this country at that time. As extrusions were not manufactured in Norway, these were produced for the Oslo firm by their associated company in this country.

With a few necessary exceptions the whole of the structure above the promenade deck was constructed of aluminium. These exceptions included the side-screens and bridge front on the promenade deck, the engine casing, No. 3 hatch trunk, staircases and lift trunks, derrick posts and derricks serving No. 3 hatch, and the boat davits. Figures 1 and 2 show the extent of the aluminium.

EXPERIMENTAL WORK

At this time no fully automatic welding machines were available, and the builders were contemplating using the semi-automatic machines. The suppliers of the extruded sections had been experimenting with a makeshift machine of their own construction which consisted of an argon-shielded consumable-electrode semi-automatic unit mounted on a self-propelled carriage. In order to gain some experience of the performance of this machine, and also to discover the amount of distortion that could be expected, it was decided to construct an experimental panel.

The material used for this panel comprised six plates 8 ft 6 in. × 6 ft 0 in. × $\frac{1}{4}$ in., to the Norwegian alloy specification B.54S (NP.5/6), and fourteen 4-in. offset bulb plates of NE.6 alloy.

The completed panel (*see* Fig. 3) was intended to represent an area of deck plating 17 ft × 12 ft with deck beams spaced 3 ft apart and connected to a deck girder. A portion of corrugated bulkhead was also welded to the underside of the deck plating.

The offset bulb-plate deck beams had welding feet attached, and it was intended to use these as permanent backing strips for the deck butts.

Plates 1 and 2 comprising panel *A* (*see* Fig. 3) were set up on a wooden jig with the butt positioned on the 4-in. offset bulb-plate stiffener. The butt was then tacked and machine welded. The plates were turned over for the machine welding of fillets *a* and *b*. Stiffener fillets, *c*, *d*, *e*, and *f* were then tacked and welded, the machine being used for *c* and *d*, whilst *e* and *f* were hand welded. The whole panel was then tested for shrinkage.

The shrinkage across the butt weld with the fillets unwelded was $\frac{1}{16}$ in.; with the fillets welded it was $\frac{5}{32}$ in. The shrinkage across the hand-welded fillets *e* and *f* was $\frac{1}{64}$ in.; there was no shrinkage across the machine-welded fillets.

For the construction of panel *B* the outer stiffeners were first welded to the individual plates 3 and 4. The plates were butt welded together using the centre stiffener as the permanent backing strip, and the latter was then fillet welded to the plate. The shrinkage across the butt weld was as follows:

	At start of run	*At end of run*
Shrinkage with fillets unwelded	$\frac{1}{32}$ in.	$\frac{1}{64}$ in.
Shrinkage with fillets welded	$\frac{5}{32}$ in.	$\frac{1}{16}$ in.

The gusset plate was then constructed and tack welded into place along the edge of panel *A*. The butt

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The author is with Swan Hunter and Wigham Richardson Ltd., Wallsend-upon-Tyne.

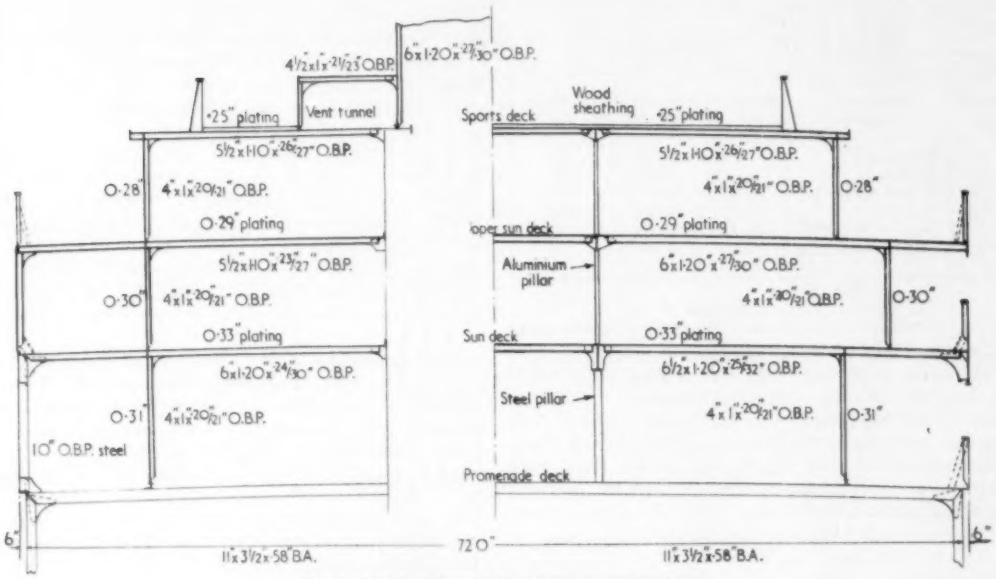


Fig. 1—Section through aluminium superstructure

of panel *B* was lined up on the gusset stiffener, and the butt welded. The gusset stiffener fillets were welded to the deck plates, and the distortion of the completed panel was measured. This was found to be less than could be expected in steel of the same scantling. The two plates comprising the corrugated bulkhead were tacked together with a stiffener forming the permanent backing bar. The bulkhead was then erected and tacked in position on the deck panel, slots being provided in the bulkhead plate to take the deck beams. The beams were welded all round at these slots, and the butt weld of the bulkhead plates was completed in the vertical position. The bulkhead was then welded to the deck panel. All the welding on this bulkhead was carried out using the semi-automatic machine.

The work on this experimental panel showed that the automatic machine, whilst not entirely satisfactory, showed definite possibilities of development. However, by the time the actual construction of the panels was commenced, a fully automatic machine

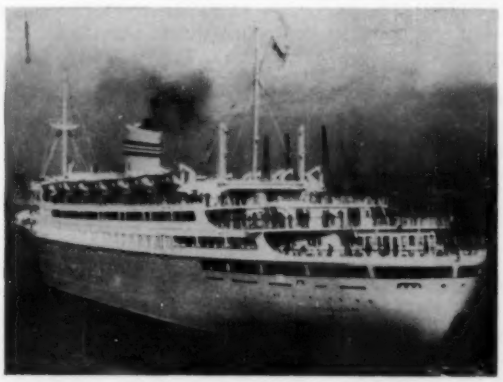
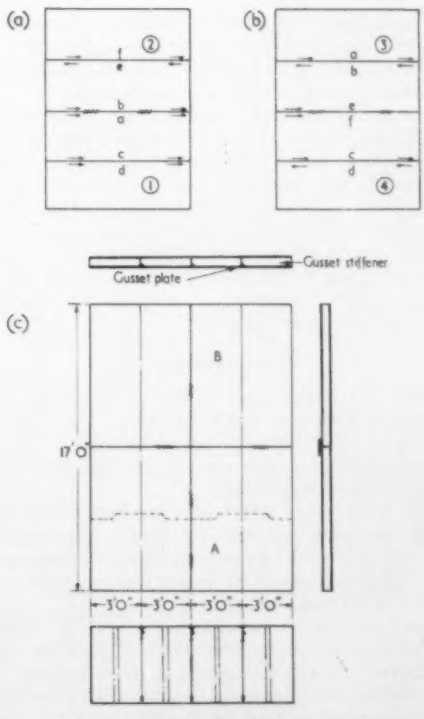


Fig. 2—General view of the *Bergensfjord*



(*a*) Panel *A* (*e* and *f* hand-welded) (*b*) Panel *B*
(*c*) Completed panel

Fig. 3—Experimental panel

Table I

RESULTS OF WELD TESTS

Sample No.	*Position of Fracture*	*Breaking Load, lb*	*U.T.S., tons/in²*	*Elong. on 2 in., %*
1	In butt weld	8750	14·65	5½
2	In plate	10,920	17·95	9
3	In butt weld	10,980	18·05	9
4	In plate	10,560	17·25	10½
5	Edge of butt weld	10,800	17·55	9½
6	Edge of butt weld	9020	17·9	9

was being produced in the U.S.A.; two of these were purchased and used with excellent results.

The panels of plating, with beams spaced 3 ft apart and supported by the girder and bulkhead 5 ft apart, flexed noticeably under the weight of a man. This difficulty was obviated by introducing intermediate beams, spaced 1 ft 6 in. apart, clear of the wood deck sheathing. The best conditions for fillet and butt welding were found to be as follows:

	Fillet Welds	*Butt Welds*
Wire dia., in.	$\frac{1}{16}$	$\frac{3}{32}$
Current, A	270	310
Open-circuit voltage	64	66
Arc voltage	26	30–32
Speed, in./min	60	25
Root gap, in.	—	$\frac{3}{16}$

Six samples of welds from the panel were submitted for mechanical testing. Each sample comprised a butt weld on to a permanent backing bar, with two continuous fillet welds sealing the edges of the backing bar. From Table I it will be seen that very good results were obtained from samples 2 to 6; sample 1 showed a lack of penetration into the backing bar, and there was a considerable drop in the U.T.S. On the basis of these results, it was considered that perfectly satisfactory butt welds could be obtained by the use of a mechanical unit, provided that conditions were such as to ensure adequate penetration into the backing bar, and to achieve this the root gap between the plates was increased from $\frac{3}{16}$ in. to $\frac{1}{4}$ in.

MATERIAL

Aluminium plates used in the construction of the deckhouses varied in thickness from $\frac{1}{8}$ in. for vent trunking to 1 in. thick for girder-face flats. The composition of all plate was to B.S. NP.5/6, and that of all extrusions to B.S. NE.6.

Offset bulb plates with a welding foot incorporated in their structure were used for deck beams and deckhouse side stiffeners; a special flat, also incorporating a welding foot, was used in association with corrugations for internal bulkheads.

Special extrusions were manufactured to facilitate the provision of permanent backing bars in way of deck butts. In way of girders a joggled flat was used, and in way of steel casings a joggled angle (*see* Fig. 4).

The sizes of aluminium plate available at the time of building were: maximum length 28 ft with 6 ft width, and maximum width 7 ft 1 in. with 24 ft 6 in. length. The superstructure overhung the midship width by 6 in. on each side, giving a total deck width of 73 ft. The deck girders were 16 ft apart, and thus the wing spans were 28 ft 6 in.; however, the length of plate required was reduced to 28 ft by adjusting the position of the joggled deck girder extrusion.

An extrusion developed for handrail stanchions consisted of a $2\frac{3}{4}$ in. × 1 in. flat with rounded corners which, in way of a half-weight bulwark plate was cut back to a square corner to assist the welding and above the plate retained the rounded finish. A kidney moulding was designed as a finishing section on the top of the plate bulwark, and also round the edge of bulwark openings and sweeps. These extrusions are also shown in Fig. 4.

The insulation of the steel/aluminium connections was a problem of primary importance. After due consideration of the various methods in use for bimetallic joints, it was decided to use galvanized steel bolts rather than aluminium or steel rivets. The bolt shank was covered with a moulded ferrule and washer of neoprene. The faying edges of the deckhouse side plates to the galvanized steel ground bar were also insulated with a neoprene strip. The steel bolts were fastened on the inboard side of the casing by the use of anti-vibration nuts, whilst the bolt head on the outboard side was separated from the casing by an aluminium washer. The nuts were spot welded to the ground bar, thus enabling any replacements necessary to be carried out from the outboard side of the casing. Other aluminium/steel connections were treated in a similar manner, and details of these are shown in Fig. 5.

PREFABRICATION

The edge preparations used for butt welds are given in Table II, and Tables III–VI show the welding conditions used.

Since adverse weather conditions would cause the dispersal of the argon gas shield, it was necessary that as much welding as possible should be carried out under cover. The obvious solution was a high degree of prefabrication, the panels being constructed in a suitably laid-out shop and transported to the ship as required for erection. The design of the deck plating and girders, deckhouse sides, bridge front plating, and as many internal bulkheads as possible, was arranged to enable as much prefabrication to be carried out as was convenient to yard conditions. The decks were prefabricated in panels which were about 30 ft square and included deck beams. The girders were arranged with the special joggled deck extrusion and the beam brackets attached at the prefabrication site. The deckhouse side panels were constructed in lengths up to 36 ft, complete with stiffeners and beam brackets. Window openings were cut and corner doublings attached in the prefabrication shop.

The amount of welding carried out during prefabrication was approximately 70% of the total welding undertaken. With this amount of prefabrication in view a shop was prepared to accommodate the necessary equipment.

On the concrete shop floor a wooden jig was set up, as shown in Fig. 6. Baulks 6 in. × 6 in., spaced 3 ft apart, were placed transversely across the shop and

Table II
EDGE PREPARATIONS FOR BUTT WELDS

Plate Thickness, in.	*Preparation*	*Root Gap, in.*	*Runs*	*Backing*
0·20	Square butt	$\frac{1}{16}$	1	Yes
0·25–0·375	Square butt	$\frac{1}{8}$	2	Yes
0·375	15° V	$\frac{1}{16}$	2	Yes
0·50	20° V	$\frac{1}{16}$	2	Yes
1·00	45° V, $\frac{1}{8}$ in. root face	$\frac{1}{16}$	6	No

Backing where used was temporary steel or permanent aluminium backing. Draw across all butts on plates $\frac{1}{4}$ in. to $\frac{1}{2}$ in. thick was $\frac{1}{8}$ in. on 2 weld runs.

Table III
CONDITIONS FOR BUTT WELDS LAID WITH FULLY AUTOMATIC MACHINES
Welding current 300 A, wire dia. $\frac{5}{32}$ in.

Plate Thickness, in.	*Runs*	*Welding Speed, in./min*		*Gas Flow,* ft³/h*
		Run 1	*Run 2*	
$\frac{1}{4}$	2	24	36	45
$\frac{5}{16}$	2	24	36	45
$\frac{3}{8}$	2	20	30	45
$\frac{1}{2}$	2	24	24	45

* Gas flow increased to 60–80 ft³/h for work on ship.

built up to suit the ship's deck camber. Across these were laid timber baulks spaced 2 ft apart. At the junctions of the transverse and longitudinal baulks, slots were cut in the upper baulks to accommodate the deck beams.

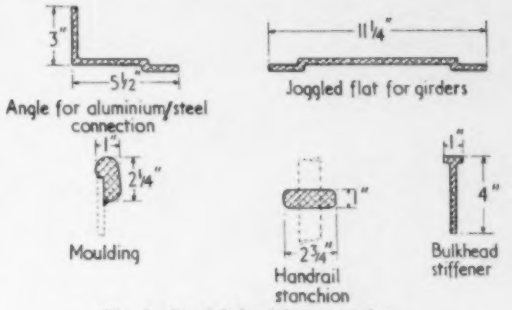


Fig. 4—Special aluminium extrusions

Alternate beams were laid in the slots provided in the wooden jig, and the deck plates were placed on top and lined up with the butt central over the beams, which were to form the permanent backing strips. The butt of the plating was then tack welded down on to the beams, care being taken to ensure that the stiffener was held hard down on the backing bar. The complete deep-penetration butt welds were then made, and the surplus weld metal was removed by the use of a caulking tool. The whole panel was then turned over and laid on a steel plate jig built up to the reverse line of the ship's camber. With the plate lightly dogged down, the fillet welds on the stiffeners were completed. The intermediate beams, clear of the deck butts, were then positioned, tacked and welded, and the whole panel was removed to the storage bay.

Fully Automatic Welding Machine

At this time, use was being made of the fully automatic machine running on portable rails which

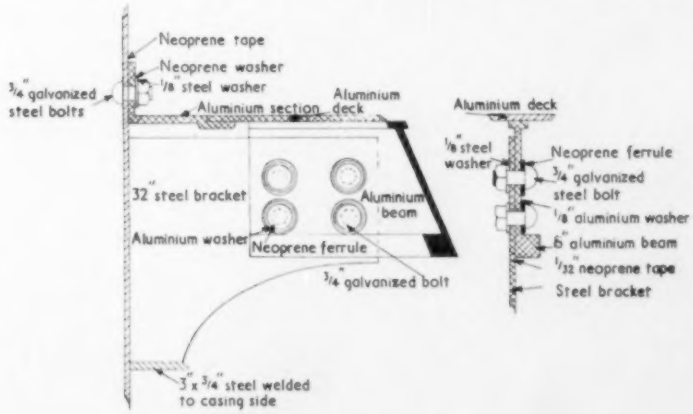


Fig. 5—Aluminium/steel connections

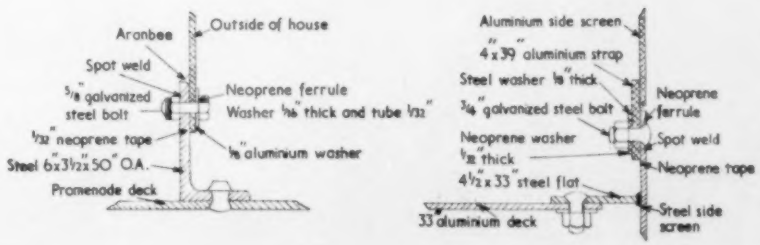


Table IV

CONDITIONS FOR BUTT WELDS LAID WITH SEMI-AUTOMATIC MACHINES

Wire dia. $\frac{1}{16}$ in.

Plate Thickness, in.	*Runs*	*Welding Speed, in./min*		*Welding Current, A*	*Gas Flow, ft³/h*
		Run 1	*Run 2*		
Flat Position					
$\frac{3}{16}$	1	20	—	230	35
$\frac{1}{4}$	2	28	28	230	35
$\frac{5}{16}$	2	26	26	230	35
$\frac{3}{8}$	2	22	22	230	35
$\frac{1}{2}$	2	15	15	230	35
1·0	6*	9 for each run		240	35
Vertical Position					
$\frac{3}{16}$	2	18	18	160	35–45
$\frac{1}{4}$	2	18	18	180	35–45
$\frac{5}{16}$	2	16	16	200	35–45
$\frac{3}{8}$	3†	12	12	220	35–45
$\frac{1}{2}$	3†	12	12	230	35–45

NOTE—Gas flow is increased to 60–80 ft³/h for work on ship.
* After 5th run, back-chip to sound metal.
† 3rd run at 10 in./min.

were laid on the panel under construction. Difficulty was encountered both in the length of time taken to line up the trackway with the beam to be welded, and also because a continual adjustment had to be made by the machine operator to counteract the changing arc lengths due to the camber of the deck panel. The problem of developing a more suitable trackway for this equipment was thus of prime importance. Manoeuvrability, speed of alignment, and the maintaining of a constant arc length were factors which had to be taken into consideration.

Table V

CONDITIONS FOR FULLY AUTOMATIC FILLET WELDING OF STIFFENERS TO PLATE

Horizontal-vertical fillets

Weld	*Welding Speed in./min**	*Leg, in.*	*Wire Dia., in.*	*Gas Flow, ft³/h*
First fillet	45–60	$\frac{5}{16}$	$\frac{3}{32}$	45
Second fillet	80–100	$\frac{1}{4}$	$\frac{3}{32}$	45

* These welding speeds were adopted to avoid cracking of fillet on first side when that on the second side was welded.

Figures 7 and 8 show the machine developed to fulfil these conditions. This comprised a built-up joist constructed to carry the welding unit and spanning the prefabrication jig. At each end of the joist was fitted a pair of wheels which ran on rails spaced 34 ft apart, running up each side of the shop. The wheels were connected to the joist through a swivel fitting which enabled the joist to be lined up with the panel under construction. The welding unit, mounted on the joist, was fitted with a floating-head attachment formed of two check plates, in which the fitting for the welding head was able to slide. The head fitting had a small guide wheel attached to the lower end, and this ran on the plate to be welded. Thus, when any local distortion occurred in the plate, it was followed by the gun fitting sliding in the check plates. An air valve was incorporated to lift the whole head fitting over the beams after welding.

This machine proved itself to be completely satisfactory, and excellent fillet welds were laid on the beams at speeds of up to 100 in./min. With the introduction of this equipment, the alignment of the welding unit on the panel became quite a simple operation.

Table VI

CONDITIONS FOR FILLET WELDS LAID WITH SEMI-AUTOMATIC MACHINE

Location	*Welding Position*	*Runs*	*Welding Speed, in./min*		*Welding Current, A*	*Gas Flow, ft³/h*
			Run 1	*Run 2*		
House sides to deck, including welding round beams: Inboard	Downhand	2	16	14	240	35
	Overhead	2	16	14	240	35
Outboard	Downhand	1	16	—	240	35–60
	Overhead	1	16	—	240	35–60
Deck beams connected at ship	Overhead	1	24	—	230	40
Beam brackets to house side stiffeners	Overhead	1	16	—	230	35
	Vertical	1	16	—	200	35
Girder webs and brackets	Vertical	2	12	12	200	40
	Overhead	2	14	14	240	40
	Downhand	2	14	14	240	40
Girder face flats	Downhand	2	14	14	240	35
Bridge front to ail decks	Downhand	2	14	14	240	40
	Overhead	2	14	14	240	40
Vent trunks ($\frac{1}{4}$ in. thick)		1	24	—	180	35

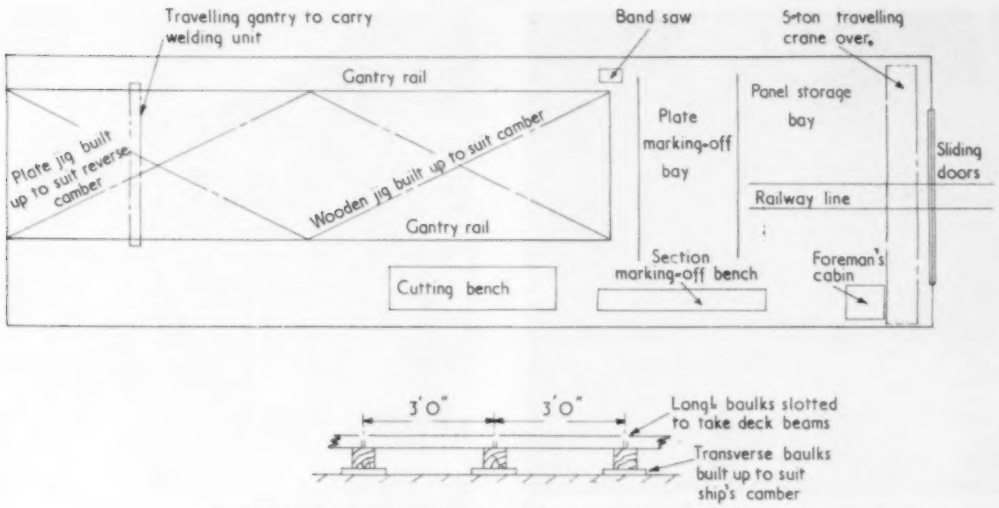


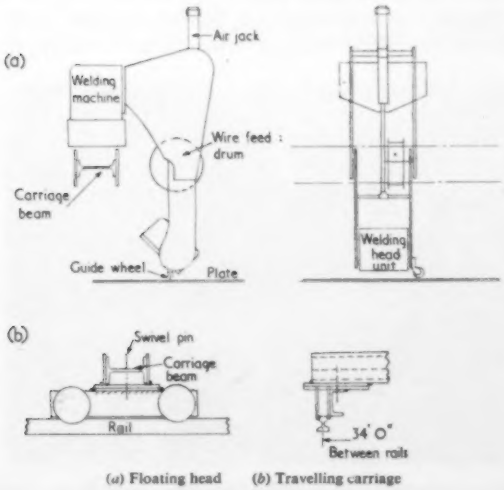
Fig. 6—Layout of prefabrication shop (*above*) and detail of jig (*below*)

Where it was necessary to weld two plates together without the use of a permanent backing bar, a temporary steel backing was provided by laying the aluminium plates to be welded on a steel plate. To hold down the edges of the plate to be welded, a special jig was constructed which comprised two channel bars with small distance chocks welded at each end. These chocks were welded to the steel base plate, the channels running parallel and spaced about 4 in. apart.

Prefabrication of Bridge Front

The construction of the bridge front structure called for special consideration from a prefabrication point of view. It was decided to construct this in five prefabricated panels, built on special wooden jigs in the shop. The jigs were carefully built up to the required shape, and the bridge front stiffeners, set as required, were laid in the slots provided. For rigidity during lifting, it was arranged that the panels should be constructed with a portion of deck plating attached. This deck plating, complete with radial beams, was also laid in position in the jig. The bridge front plates were cut, rolled to shape, and placed in position with their butts on the stiffeners, which served as backing bars.

Each of the five bridge front prefabricated panels was constructed on a separate jig (*see* Fig. 10), and transported by crane to the ship for lifting into position. Figure 11 shows the first bridge front panel erected at the ship, and Fig. 12 the bridge front with all the panels in place.



(*a*) Floating head (*b*) Travelling carriage

Fig. 7—Welding machine

ERECTION

The deckhouse sides of the promenade deck, and the sun deck girders, were erected at the ship, and retained in position by shores and wires. Across these were laid the prefabricated panels of the sun deck plating complete with beams. This procedure was

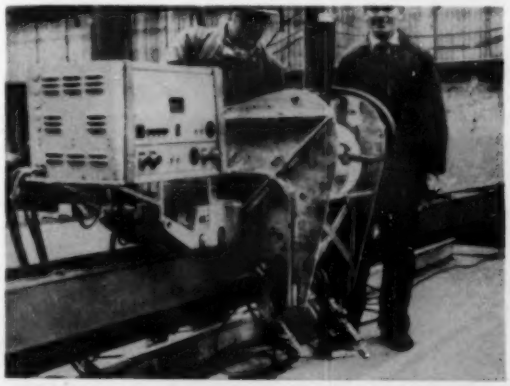


Fig. 8—Automatic welding machine

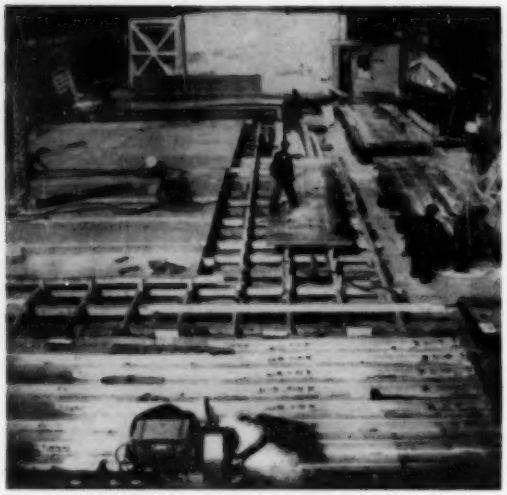


Fig. 9—General view of prefabrication shop

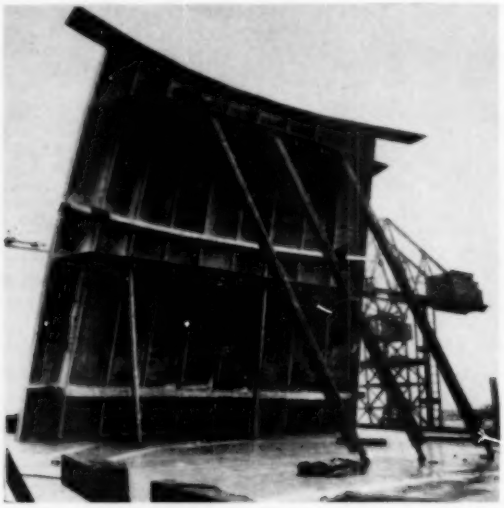


Fig. 11—First panel of bridge front structure erected at ship

followed throughout the erection of the aluminium structure. Figures 13, 14, and 15 show views of the structure during erection.

The welding of the aluminium on the ship had its own problems as compared with the shop welding. Atmospheric conditions affected the efficiency of the welding, and great care was taken to obviate this difficulty. The plates were carefully inspected, and any water, oil, or dirt was removed. Portable screens were arranged to keep off the worst of the wind, which tended to disperse the argon shield and cause inefficient welds to be laid.

As a further precaution against the wind, the rate of the argon flow was increased, and this proved most satisfactory in retaining an effectively shielded arc. Argon consumption in the shop work was 30–35 ft^3/h for semi-automatic welding, and 45 ft^3/h for fully automatic welding. At the ship, both semi-automatic and fully-automatic welding consumed an average of 60 ft^3/h, with a maximum of 80 ft^3/h.

Semi-automatic consumable-electrode welding units, with both air-cooled and water-cooled torches, were used for the erection work. A water supply and drainage system had to be evolved at the ship to enable the units incorporating water cooling to operate successfully. The water supply was led from a mains extension at the ship's side on to the deck, where flexible hose carried it to the welding unit. Small portable drains were stationed at intervals along the deck, capable of being reached by a reasonable length of drain hose from the unit. The water from each drain ran into an overboard discharge pipe.

In all, twenty welding units were used in the construction of the aluminium deckhouses; this total was made up of two fully automatic and eighteen semi-automatic machines.

TRAINING, INSPECTION, ETC.

Before work commenced on the welding of the deckhouses, there were no welders experienced in the

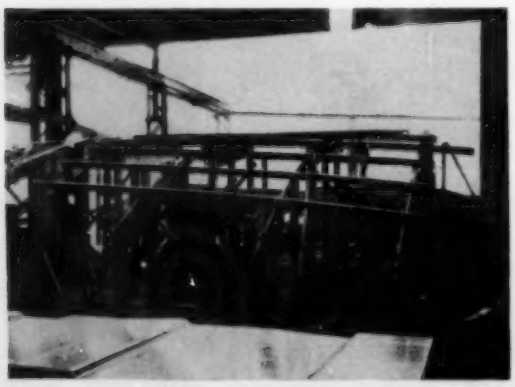


Fig. 10—Bridge front prefabrication jig with bridge front stiffeners in position

Fig. 12—General view of bridge front with all panels erected at ship

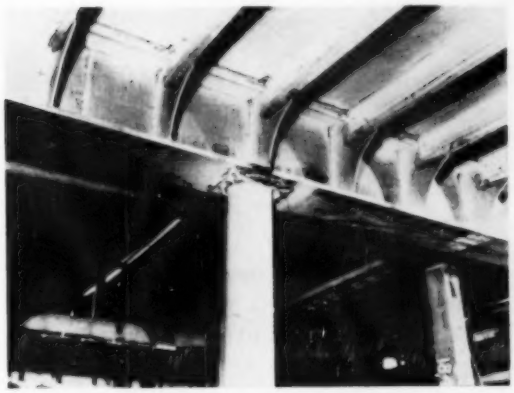


Fig. 13—Detail of girder bracket connection to beam

Fig. 15—View on upper sundeck with house sides in position

type of work to be undertaken; however, with the practical experience obtained from the work on the experimental panel a nucleus of efficient welders was formed. As the work on the prefabrication of the aluminium structure proceeded, and more welders became necessary, these were trained; initial training was given in the welding school, and they then gained experience in tacking work before starting on full production. A total of 32 welders were trained in the welding of aluminium.

In the initial stages, all the work was being done in the shop, where conditions were reasonably good and interference through draughts was reduced to a minimum. This provided ideal groundwork for the welders who, after gaining much experience in the shop, moved out on to the ship.

The radiographic inspection of the butt welds was hindered by the presence of the backing bar. At the beginning of the constructional work samples of the welds were taken and these proved to be satisfactory. As work proceeded, the welding was inspected visually.

No detrimental effect from fumes was experienced throughout the welding of the aluminium. The danger to the eyes from the arc flash was practically eliminated by the issue of industrial anti-flash goggles to all those engaged on the prefabrication, and a special dark glass was used for those actually employed in welding.

Fig. 14—View on sundeck showing girders and deckhouse side panels being erected

The preparation of the aluminium structure for painting was carried out as follows. The plate was degreased and an etch primer coated on by using a combined degreasing and etching preparation. This was followed by the application of two coats of zinc chromate paint, after which the normal finishing paints were applied. All aluminium/wood connections, such as wood decks and wood bearers on aluminium seatings, were treated by coating the faying surfaces with zinc chromate.

Welding production on the ship was hindered to a certain extent by the weight of the equipment, and the sensitivity of the welding machine. Owing to the need to move the machines from job to job, and because of their delicate nature, it was found of the 18 semi-automatic machines an average of 3 machines were constantly out of production and awaiting maintenance. Weather conditions varied throughout the building of the *Bergensfjord*, from a very warm summer to the depths of a bitter winter. The builders took full advantage of the fine summer to erect most of the exposed aluminium structure, but some finishing off work had to be done in conditions which included snow, frost, and high winds. In some cases ice had to be chipped away and the structure dried before welds could be successfully laid. Owing to the freezing of the water supply, the use of water-cooled welding guns had to be dispensed with, and these were replaced with air-cooled guns.

The total weight of filler wire consumed in the construction of the aluminium structure amounted to 10 tons 3 cwt. The amount of argon used to supply the inert gas shield to the welding units was 576,400 ft^3. The returned figure for welding labour on the aluminium structure was 220 man-hours/ton.

ACKNOWLEDGMENTS

The author would like to thank the management of Swan, Hunter and Wigham Richardson, Ltd. for their helpful co-operation in the preparation of this paper. Thanks are also due to Mr. Eland, who was the welding foreman on the aluminium structure, for his assistance particularly in the compilation of the welding tables.

INTERNATIONAL INSTITUTE OF WELDING

COMMISSION III: *Resistance Welding*

RESISTANCE WELDING PARAMETERS

Contribution to the Study of the Control of the Parameters Voltage, Current, Pressure, and Time in Resistance Spot Welding

By M. Evrard and C. Haslé (France)

Introduction

An understanding of welding parameters is important in resistance spot welding. Numerous studies have been made on the subject, and varying methods of determination have been proposed.

A comparative examination of the available procedures, especially for the determination of the secondary current, has been presented by Quint.*

Most of the solutions proposed are not absolutely satisfactory, either because of the complexity of the apparatus required, or because of the inaccuracy of the results obtained.

The (French) Institute of Welding has been investigating methods which give accurate results and can conveniently be employed in current practice. Thus, for example, for the measurement of welding times of machines giving an alternating secondary current, a simple solution has been published by Gaubert and Riedinger.† This method has since been perfected by the addition of recording devices of an elementary type.

More recently, in an investigation on the spot welding of ordinary rolled steels to determine the effects of surface conditions, the laboratories of the (French) Institute of Welding have been experimenting with methods of recording and measuring welding parameters, a description of which is given below, together with some examples of results. The equipment used has made possible the simple, simultaneous, and immediate control of the welding parameters where single-phase welding machines are used.

METHOD OF MEASUREMENT

The method depends essentially on the employment of a recording oscillograph, connected to devices by which the voltage, current, and force are respectively determined as a function of time (Fig. 1).

Recording Oscillograph

The oscillograph used, which was of a special type,‡ can record 8 parameters simultaneously. Stylographs record the variations on a 35-mm film, coated with a layer of carbon 0·1μ thick; the movement of the film can be regulated at 1, 2, 4, or 8 cm/s. The driving mechanism is such that the film reaches its set speed in about 0·02 of a second.

The curves can be examined immediately after being recorded, by means of an optical enlarger, the image appearing on a ground-glass screen. By spraying a very dilute cellulose varnish on the film, the recorded traces can be fixed and satisfactorily preserved. The lines of the traces are of strictly uniform thickness of the order of 0·01 mm. The measuring equipment controlling the stylographs consists of moving-iron galvanometers, the response of which is 850 c/s; this permits, without inertia, the recording of periodic phenomena of frequencies up to 700 c/s. The rating of each galvanometer is chosen according to the recording to be made. Moreover, an amplifier or a bank of resistances can be placed in the supply circuit of the measuring equipment, to regulate its current to appropriate values in relation to the values to be measured.

The amplitude of the traces is of the order of millimetres with a.c. and about 0·5 mm with d.c. This amplitude may appear slight, but since the breadth of the lines is of the order of 0·01 mm, an appropriate optical enlargement allows accurate and easy reading of the diagram.

VOLTAGE MEASUREMENT

The object of this investigation is to determine, by means of voltage measurements, the variation of the impedance of the workpiece placed between the electrodes during a spot welding cycle. For the results to be significant, the voltage must be measured between points as near the tips of the electrodes as possible, thus reducingthe term L_ω of the impedance measured to a minimum.

The connection with the galvanometer is effected by means of an a.c. amplifier.* The measuring equipment has a rating of 10 mA, 75 V. The amplifier is necessary because the voltage between electrodes during welding is only a few volts.

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* M.J. QUINT: 3rd International Congress of Electro-Heat, 1953.

† A. GAUBERT and U. RIEDINGER: *Soudage Tech. Conn.*, 1955, vol. 9, No. 5/6, p. 147.

‡ *See* R. DUBUSC: *Bulletin de la Société Française des Electriciens*, 1953, Oct., 7ème série, vol. III, No. 34.

* The coefficients of amplification used are 75V/2, 5V, and 75V/5V.

Abridged and edited version of I.I.W. Document III–58–56. Copies of the complete authorized report may be had from the Technical and Scientific Secretariat of the I.I.W., 32, Bd. de la Chapelle, Paris (18e).

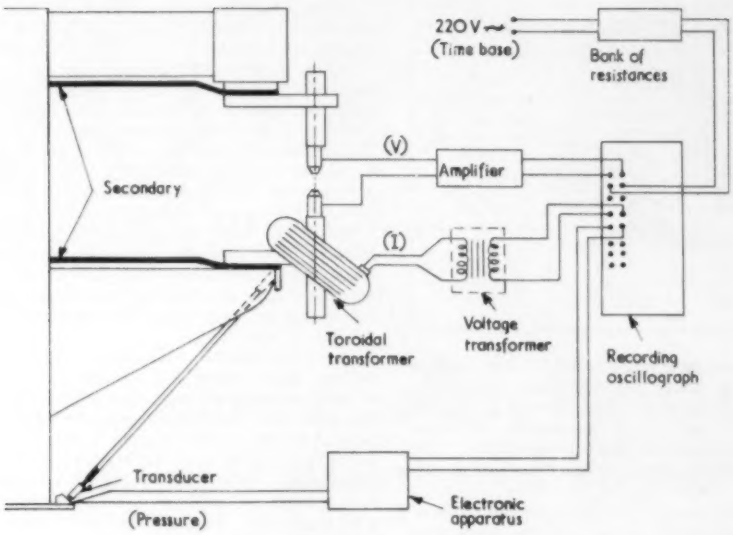

Fig. 1—Diagram of recording apparatus

CURRENT MEASUREMENT

For the measurement of current, a toroidally wound current transformer is used; the band pass of this transformer goes down to 2 c/s, which allows the restitution of the aperiodic components.* This transformer is placed around the electrode holder (*see* Fig. 1). Its ratios are 2000, 5000, 7500, and 10,000/5 A r.m.s. For currents above 10,000 A it is necessary to add a second voltage transformer in parallel, of which the ratios of transformation are 2, 4, and 10, the current delivered to the secondary always corresponding to a rating of 5 A.

The one or two transformers are connected to a galvanometer with a rating of 1 A, 0·75 V, which, when shunted by a resistance, gives it an apparent rating of 5 A r.m.s.

With such an apparatus, it is possible to measure currents ranging from 2000 to 100,000 A r.m.s., which amply covers the ranges normally used in resistance spot welding. For successive measurements, in the case of maximum current and for purposes of heating, the duty cycle admitted is 0·1 s on and 10 s rest.

Figure 2 illustrates the recording obtained on a single-phase welding machine, provided with an electronic timing device. The length of the zero pause t between two successive half-cycles depends on the phase shift applied to the ignitrons.

* This toroidal transformer was designed to make it possible to record the welding currents of three-phase electronically controlled machines.

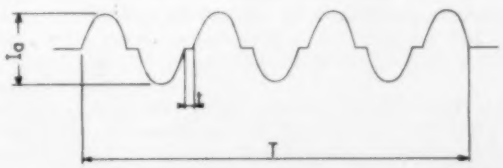

Fig. 2—Recording of current from single-phase welding machine

From these curves, it is possible to determine the effective welding current by approximating each half-cycle to a sine wave. In these conditions, if T corresponds to the total time taken for passage of the current, t to the idle time between each half-cycle, and if the curve recorded contains n zero pauses, the effective current I is given by the formula:

$$I = I_a \sqrt{\frac{T - nt}{T}}$$

in which I_a is the r.m.s. value of a sinusoidal current of an amplitude equal to that of the curve recorded.

PRESSURE MEASUREMENT

Use of Electric Resistance Strain Gauges—Strain gauges were used in preliminary tests. They were fixed to the upper arm of the resistance welding machine, two being in compression and two in tension.

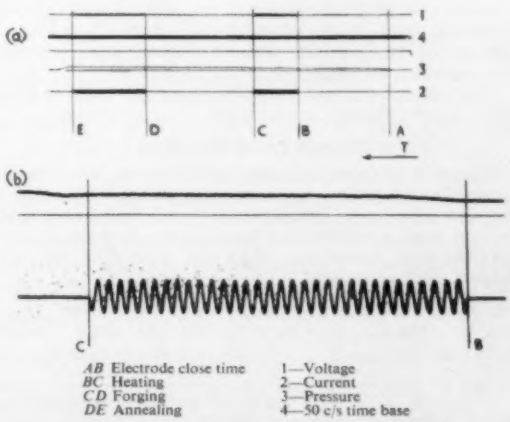

Fig. 3—(*a*) Example of record of parameters and (*b*) enlargement of section *BC*

Table I
RESULTS OF COMPARATIVE TESTS

	Energy, %	*Ammeter Reading, A*	*Current measured from Record, A*
First setting of transformer	52	12,120	12,720
	64	13,500	14,300
	76	14,480	15,120
	100	15,520	16,100
Second setting of transformer	52	16,250	17,130
	64	18,240	18,980
	76	19,200	20,420
	100	19,900	21,350

The curves thus obtained require careful interpretation, because the recordings were seriously disturbed at the moment of the passage of the welding current, as a result of induced current in the gauges themselves. Different methods were tried to eliminate these disturbances; none gave complete satisfaction, and the use of strain gauges was abandoned.

Use of an Electro-Mechanical Transducer—The apparatus used consists essentially of an electro-mechanical transducer; this can detect very small displacements, which are communicated to a piston plunger and cause a variation of mutual induction between two coils connected in series.

The transducer was mounted on the base of the frame of the welding machine and the displacement of the lower arm of the machine was transmitted to it by means of a rod of adjustable length, fixed immediately below the electrode holder (*see* Fig. 1). This arrangement was adopted in preference to placing the transducer in a fixed position and in continuation of the electrode itself, to prevent its recording the movements of the machine in relation to ground, at the same time as the displacement of the lower arm. The connection between the transmitting rod and the head of the transducer should be made by means of insulating material, so that no induced current passes across the transducer. Also, to eliminate any influence of the magnetic field created by the welding current, the transducer was placed in a shield of sheet steel, with a hole for the transmitting rod.

Apart from the transducer, the equipment for measuring the displacement of the lower arm consists of an electronic apparatus comprising a low-frequency generator giving a carrier wave of 8000 c/s, and an amplifier. A voltage proportional to the displacement of the arm is transmitted to the galvanometer (rating 500 mA, 1·5 V) which actuates the recording oscillograph.

The curves obtained from this apparatus are free from all inductive interference from the welding current.

EXAMPLES OF RESULTS

Figure 3 gives an example of curves recorded simultaneously for voltage, current, pressure, and time, during the making of a spot weld between steel sheets with satisfactory surface conditions, the welding cycle comprising the following operations: electrode close time, heating, forging, and annealing.

Curve 1 represents the voltage; in the case shown, the variations in amplitude are small, from 1·6 to 2·4 V in heating, and from 1·05 to 1·65 V in annealing.

Curve 2 is that of the current. The r.m.s. value of current deduced from this curve, by the method previously indicated, is 16,880 A for heating and 14,100 A for annealing.

Curve 3 shows the pressure cycle. The pressure of the compressed air supplied to the machine was regulated at 4·2 kg/cm² when the electrodes were brought together and at 6 kg/cm² for forging, corresponding to an electrode force of 750 kg and 1080 kg respectively.

This curve shows the fairly rapid increase of force at the moment of heating and the more gradual increase which occurs during the forge time. This anomaly appears to be connected with the thermal expansion of the metal due to the passage of the current. This question is at present being studied in more detail.

Curve 4 is the record of mains voltage of 220 V at 50 c/s, and has been used as a time base.

As regards the measurement of current, some comparative tests have been made to verify whether the proposed method results in any important errors.

The instrument used for these tests was a moving-iron ammeter of substandard quality, using a rating of 5 A, which is of a type less susceptible to harmonics. Measurements were made with the electrodes in short circuit and current passing for 3 s, to enable an accurate reading to be taken on the ammeter. The arrangement was similar to that shown in Fig. 1, with the addition of the ammeter connected in series between the oscillograph and the current transformer.

In the case of an electronically controlled single-phase welding machine, it is possible, with single setting of the transformer of the machine, to obtain several values of secondary current, effected by the phase shift applied to the ignitrons. For the comparative tests, two settings of the transformer were used, and for each, four settings of the ignitrons. The results obtained are given in Table I. The measurements made by the two methods vary by about 4–7%, according to the settings. This variation probably results from the difficulty of taking a very precise reading with the type of ammeter used, in spite of the current passing for three seconds.

CONCLUSION

The tests described show that the recording oscillograph is perfectly well adapted to recording the measurements required in resistance spot welding. The simultaneous recording and immediate examination of the curves obtained makes possible an effective control of the various parameters during welding. A method of obvious value for any fundamental study concerning resistance spot welding is thus available.

Moreover, industrially, use of this apparatus, which is not fragile and is easy to use, makes it possible to verify that the setting of the machines remains sufficiently constant. The fact that the curves are recorded means that they may easily be subsequently examined, which is a great advantage.

It should be stressed that, in the case of 50-cycle machines, the parameters can be controlled with satisfactory precision by reasonably simple means if the complete apparatus described in the paper is not available.

Welding

RESEARCH

The Influence of Surface Films on the Pressure Welding of Metals

By R. F. Tylecote, D. Howd, and J. E. Furmidge

SYNOPSIS

FROM the results of earlier work it appeared that the ratio of the hardness of the oxide film to that of the metal might be an important factor determining the pressure weldability of metals.

The following work was carried out to discover how far this hypothesis was correct, and to make use of it where possible, to improve weldability by suitable alloying additions.

In general, it may be said that the metal hardness that is important is that of the surface just before welding begins to become effective, i.e. in the case of work-hardenable metals the hardness after a certain degree of cold work has taken place.

It is shown that the ratio of oxide-film hardness to the hardness of the metal before welding only gives an indication of pressure weldability when the metal work-hardens slightly or not at all and when it possesses a film thicker than about 50A. In the cases where the film is very much thinner than this, or the metal is extremely work-hardenable, this simple theory does not hold.

Not only does elastic recovery assume greater importance in the work-hardenable alloys, but the continuous plastic yielding which is necessary for the break-up of the film is much reduced, thus resulting in a decrease of weldability and a reduction in the importance of the properties of the surface film.

Introduction

As a result of previous work done on the pressure welding of pure metals[1] and on the friction of sliding metals,[2, 3] it appeared that there might be some connection between weldability, i.e. the ease with which welding occurred as deformation was increased, and the relative hardness of the surface film and the metal.

It is certain that to get metal-to-metal contact and hence pressure welding, the thin films which exist on metal surfaces after scratch-brushing must be ruptured to a greater or lesser degree. The asperities on one of the roughened surfaces will be pressed against hollows or asperities on the other, and local deformation will take place, resulting in a change of contour of the asperity, and it is hoped, rupture of the film. Alternatively, in the case of dissimilar metals, it would be possible for a hard asperity to puncture the film on a soft metal, but in so doing it might fail to rupture the film on itself.

Whereas it has been shown that there is a good correlation between sliding friction and the oxide/metal hardness ratio, it was not at all certain that the parameter of hardness was the operative factor in causing film breakdown under pressure-welding conditions. Under these conditions resistance to failure by stretching or the elasticity of the film would be expected to be the more important factor. Since this factor cannot be measured directly in the case of thin oxide films, it was hoped that hardness might bear some relation to it. The following work, therefore, is an attempt to determine to what degree the oxide/metal hardness ratio influences weldability.

REVIEW OF INFORMATION ON THE HARDNESS OF OXIDES AND ITS EFFECT ON FRICTION

In experiments on the effect of load on the coefficient of sliding friction of metals, Whitehead[2] found that in the case of copper the coefficient did not remain constant as demanded by Amonton's law but, at some critical load, increased from a consistently low value to a consistently high value. A change in the character of deformation in the track of the slider was noticed when the critical load was exceeded. It appeared that the low coefficient was due to the slider

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Table I
LOADS TO ESTABLISH METAL CONTACT

Metal	*Hardness, kg/mm²*		*Load at which appreciable metal contact occurs, g*
	Metal	*Oxide*	
Gold	20	—	0
Silver	26	—	0·003
Tin	5	1650	0·02
Aluminium	15	1800	0·2
Zinc	35	200	0·5
Copper	40	130	1
Iron	120	150	10

moving on top of a surface film which was acting as a boundary lubricant, while the high coefficient, and consequent change in the character of deformation, was due to formation and tearing of metallic junctions by a ploughing effect.

In the case of silver and aluminium no such change in the coefficient was found over a range of load of from 0·01 g to 4 kg. The coefficient for silver was consistently high, while that for aluminium was also high. In the case of silver it was believed that the film was too thin to prevent 'ploughing', while with aluminium intimate contact of metal and oxide occurred due to the breakdown and embedding of the thin brittle film in the softer metal beneath.

Whitehead explained the difference in these results by the ratio of oxide to metal hardness, which for copper is nearly unity, whereas for aluminium it is of the order of 3·5–4·5.

On copper, it is possible for the metal and oxide to undergo plastic deformation together if the deformation is sufficiently small. With aluminium, the metal will deform below the film, and therefore undermine the film causing its disruption.

Bowden and Tabor[3] have extended this work, and Table I shows the loads at which appreciable metal contact occurs. In the case of tin and aluminium the oxide is hard and brittle and contact takes place at comparatively low loads, while with zinc, copper, and iron the oxide is soft relative to the metal and contact does not take place so readily.

Moore and Tegart[4] investigated the effect of metal hardness on the coefficient of friction of a copper–beryllium alloy. This alloy could be expected to possess a film of BeO with a hardness of 1700 kg/mm.[2] The metal hardness was varied by solution-treating the alloy by quenching in cold water from 800°C and heating one end up to 400°C so that there was a

Table II
VARIATION OF HARDNESS RATIO WITH COEFFICIENT OF FRICTION

Metal Hardness, D.P.N.	*Coefficient of Friction, μ*	*Ratio* $\frac{\text{D.P.N. Oxide}}{\text{D.P.N. Metal}}$
120	1·1	14·0
200	0·9	8·5
400	0·4	4·2

Table III
MOHS'S HARDNESS OF METALLIC OXIDES

Oxide	*Calculated (Friederich)*	*Experimental Values*	*Reference*
Al_2O_3	8·7	9	Finch[6]
Fe_3O_4	6·7	6·5	,,
Fe_2O_3	7	6·5	,,
NiO	7·5	5·8	Dies[7]
MnO	5·5	5·5	Finch[6]
Mn_3O_4	6	5·5–6	,,
TiO_2	7·3	6–6·5	,,
MgO	6·3	6	Dies[7]
ZnO	5	4·3	,,
PbO	3·8	2	,,
CdO	3–4	3	Finch[6]
ZrO_2	6·5	6·5	,,
Sb_2O_3	4	2·5	,,
Bi_2O_3	4·3	4·5	,,
HgO	4·3	1·5	Phillips[8]
Cu_2O	3·8	3·7	Dies[7]
SnO_2	6·8	6·7	Dies[7]
SnO	4·3	4·9	Tylecote[1]
GeO_2	8·5	—	
Ga_2O_3	6·5	—	
Li_2O	5·0	—	
Tl_2O	3·0	—	
Tl_2O_3	5·0	—	
BeO	8·8	—	

gradual transition from a soft solution-treated structure to an over-aged structure. The area of maximum hardness of 400 D.P.N. coincided with the minimum coefficient of friction using a steel ball of hardness 464 D.P.N. as a slider.

The results are given in Table II and show that as the hardness ratio increases the coefficient of friction also increases.

Table IV
HARDNESS OF METALS AND OXIDES AND RESULTING HARDNESS RATIOS

Metal	*Hardness of Metal, D.P.N.*	*Oxide*	*Hardness of oxide, D.P.N.*	*Hardness ratio, Oxide/Metal*
Lithium	0·5	Li_2O	*110*	220
Thallium	2·7	Tl_2O	35*	50
Mercury	4†	HgO	*5*	1
Bismuth	7·1‡	Bi_2O_3	*450*	63
Lead	4·5	PbO	*23*	5
Indium	2	In_2O_3	800	400
Magnesium	41	MgO	550	13
Aluminium (super-purity)	20·8	Al_2O_3	1800	87
Aluminium (commercial-purity)	41·9	Al_2O_3	1800	43
Tin	9·6	SnO	*380*‖	40
Copper	39·5	Cu_2O	160	4
Iron	72	Fe_2O_3	670	9
Silver	29	Ag_2O	135*	4·7
Zinc	60	ZnO	250	4·2
Cadmium	20	CdO	80	4
Nickel	98	NiO	480	4·9
Lead	4·5	PbO	23	5

* Calculated from Friederich's relationship
† From Wood and Von Ludwig[10] at −93°C
‡ At 95°C
‖ Tylecote[1]

Oxide hardnesses that have been determined experimentally by the authors are italicized.

Since a high coefficient of friction in metals is caused by the production of welded junctions, it would be expected that the conditions causing maximum friction would also be the best from the point of view of pressure welding. This would indicate that the hardness of surface films on metals, which may be oxides, sulphides, or carbonates, should be as high as possible. Unfortunately very little information is available on the hardness of these films, and what little there is has been obtained on impure minerals and is expressed in terms of Mohs's scale.

Mohs's hardness scale is generally regarded as being the most inferior of the scratch-hardness scales, since there is no constant relationship between the hardness of the standard substances used in the scale. If Mohs's scale is compared with a linear scale of indentation hardness, the difference in hardness between 9 and 10 on Mohs's scale is greater than the difference between 0 and 9. Furthermore, the process of film breakdown during pressure welding is essentially one of breakdown by indentation rather than by scratching as in the case of metallic sliding friction.

Whereas the Mohs's hardness of the common minerals is known, the hardness of the rarer metallic oxides has not been determined. In order to get some indication of metals with hard oxides, use has been made of the relationship shown by Friederich[5] mentioned in an earlier paper.[1]

Table III gives values of the hardnesses of some metallic oxides calculated from Friederich's relationship compared with values determined experimentally by various workers. The hardnesses compare quite well, and the agreement certainly seems to be good enough to warrant the use of this relationship as a tentative guide.

An attempt has been made to convert the hardnesses in terms of Mohs's scale to indentation hardnesses by using figures obtained by the U.S. Bureau of Standards and quoted by Hoyt.[9] Use has been made of them in all cases where the original measurements have been in Mohs's scale.

As a result it has been possible to draw up Table IV giving the hardnesses of the metals as measured, and those of the oxides either as measured or calculated from Friederich's relationship. In order to complete this table, so far as the projected work was concerned, the hardness of some of the oxides was determined by the authors.

The oxide/metal hardness ratios given in the last column of Table IV show that, if Whitehead's theory is applicable, the metals Li, Tl, Bi, In, Al, and Sn would be expected to weld comparatively well, while the metals Zn, Ag, Pb, Cd, Cu, Fe, and Ni would be expected to be more difficult to weld. This assumes the presence of an oxide film of sufficient thickness. In many cases the composition of the film formed in normal atmospheric air at room temperature is not known with any degree of certainty. In the case of silver and copper, sulphide films may be present in addition to oxide films. In some cases the oxide films may be hydrated, in others carbonate films may be formed.

EXPERIMENTAL TECHNIQUE

Preparation of Materials

The pure metals were obtained from various sources of supply and were either high-purity or commercial-purity, as shown in Table V. The alloys were made up in the laboratory by using the respective pure-metal and high-purity alloying elements. In certain cases fluxes were used. Pure cadmium was melted in a gas-fired furnace using a $ZnCl_2$ flux, whereas the Cd–Mg alloys were melted under a $MgCl_2$ flux as used by Hume-Rothery and Raynor.[11]

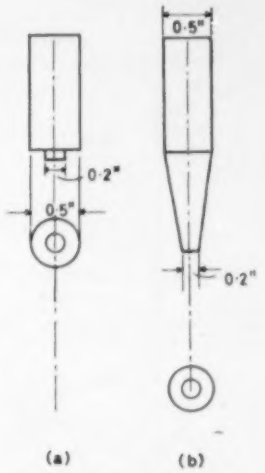


Fig. 1—Types of tools used

Pure zinc, pure cadmium, and the Zn–Al alloy were hot-rolled at 200–160°C. The Ag–2% Al alloy was cold-rolled in the solution heat-treated condition since it was found that intermediate annealing treatments introduced brittleness.

The Zn–Cd alloy could not be hot- or cold-rolled but was satisfactorily hot-forged at 150°C and then hot-rolled with intermediate reheats. Annealing this material after rolling was found to induce embrittlement.

Commercially pure bismuth was melted under a flux of potassium nitrate and sodium hydroxide, and the metal was then chill-cast into 0·5 in. thick sheet. This sheet was cut into strips of section $\frac{1}{2}$ in. $\times \frac{1}{8}$ in., and was then reduced to sheet 0·05 in. thick by hot-pressing. This was done by cutting the $\frac{1}{8}$ in. thick strip into $\frac{1}{2}$-in. portions, and then each portion was sandwiched between flat, stainless-steel tools fitted to the hot press.[12] The temperature of the tools was maintained at 170–200°C. The bismuth was easily reduced to sheet 0·05 in. thick. Each small sheet provided sufficient material for two strips for welding.

All the other alloys behaved normally and could be reduced by hot- or cold-rolling down to the required thickness, i.e. 0·050 in.

Welding Technique

In order that the results of this work might be compared with the previous work, lapped sheet specimens and two circular pressure-welding tools, 0·20-in. dia. (*see* Fig. 1*a*), were used. The pressure welds were made on strips 0·05 in. thick × 3 in. long and from 0·5 to 0·75 in. wide. The length of the strips was reduced in the cases of lithium and thallium in order to save

Table V
PROPERTIES OF METALS AND ALLOYS USED

	Purity	*Alloy elements, %*	*Hardness of metal, D.P.N. (at R.T.)*	*Condition when welded*
Zinc	99·995%	—	39 D.P.N. (5 kg)	Annealed
Zinc–Al 1%	,,	1·2	52 ,, ,,	,,
–Cu ½%	,,	0·5	48 ,, ,,	,,
–Cd 2%	,,	—	60 ,, ,,	As rolled
–Al 5%	,,	5·0		
Cadmium	"Chempur"	—	21 ,, ,,	Annealed
Cadmium–Zn 2%	,,	—	24 ,, ,,	Annealed
–Mg 5%	,,	4·5	54 ,, ,,	Hot rolled
–Mg 1%	,,	0·4	25 ,, ,,	,, ,,
Tin	99·99%	—	13 ,, ,,	As rolled
Bismuth	Commercial	—	7·1 D.P.N. (1 kg) 95°C	
Lead	Ex Cookson, Commercial	—	4·5 D.P.N. (1 kg)	
Mercury	Commercial	—	4·0 D.P.N. –93°C	
Thallium	Ex Johnson Matthey Co.	—	2·7 D.P.N. (1 kg)	
Lithium	Ex Johnson Matthey Co.	—	0·5 (Brinell)	
Indium	99·9%	—	2·3 (Micro 10 g)	
Silver	Fine 99·9%	—	30 D.P.N. (5 kg)	Annealed
Silver–Al 5%	,, ,,	4·7	75 ,, ,,	,,
–Al 2–	,, ,,	1·9	40 ,, ,,	,,
–Cu 1%	,, ,,	—	38 ,, ,,	,,
Copper	T.P. Electrolytic		46 D.P.N.	,,
Copper	Cathode		48	,,
Copper–Al 2½%	Al 99·992%	2·5	62	,,
Aluminium	Commercial	—	55	Fully hard
	Purity approx. 99%	—	20	Annealed
S.A.P. (Sintered Aluminium Powder)	—	Al_2O_3	110	As received

metal. In the case of bismuth a hot press tool was used, similar to that used previously.[12]

The technique used in making a weld at room temperature was to take the two strips to be joined, thoroughly de-grease them with carbon tetrachloride, and then scratch-brush the weld areas with a rotary wire brush fitted to a ⅓ h.p. electric motor. In some cases a fine scratch brush with a surface speed of 1580 ft/min was used. In others, a coarse wire brush (wire diameter 0·011 in.) was used with a surface speed of 1490 ft/min. Brushing was carried out to remove the original surface film and roughen the metal surface without undue heating. The surfaces were then put together and placed between the tools in a press, and pressure was applied to give the required weld deformation. The time between scratch-brushing and welding was less than 15 s, except where stated otherwise.

In the case of the impact experiments, a drop-hammer was used weighing 29 lb and falling through a height varying from 6 in. to 3 ft 6 in. A single tool, the shape of a truncated cone of diameter 0·5 to 0·2 in. was used in the hammer (Fig. 1*b*), the anvil being perfectly flat.

Oxidation

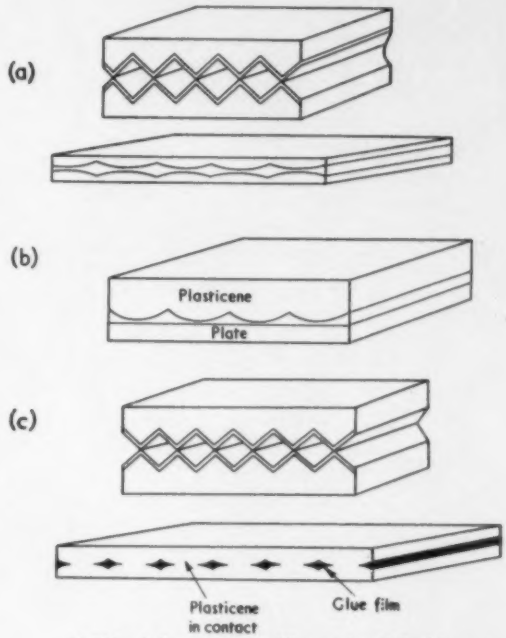
The oxidation experiments were carried out on a semi-microchemical balance which had an accuracy of ±0·01 mg, capable of taking a maximum load of 20 g. The balance was placed in a room, which, although not thermostated, showed only a slight temperature variation of ±1°C on a mean temperature of 18°C. The temperature variation over several weeks was measured by a thermograph, but no measurements were made of the relative humidity which would be fairly high (50–95%).

Strip specimens about 0·010 in. thick by 17·3 cm long by 2 to 2·8 cm wide were de-greased, weighed, fixed to a piece of thin board, scratch-brushed, loosely

coiled using forceps, and placed on the balance pan. Adjustment was made for the weight loss due to scratch-brushing and then readings were taken at suitable intervals, i.e. every minute for the first half hour, and then every five minutes. After the first hour or, in some cases, an hour and a half, the scale reading was autographically recorded with a camera.

Estimates of film thickness were calculated on the basis of two assumptions. These were (*a*) a specific chemical composition for the film and (*b*) a given roughness ratio, i.e. the ratio of the true surface area and geometrically measured surface area. As to the first assumption, in the present calculations anhydrous oxides have been presumed to be present, but in the atmosphere used, the presence on lead of some type of basic carbonate, or of a 'mixed' sulphide-oxide film on silver, or of hydration cannot be excluded. Indeed, a basic carbonate seems more probable than a simple oxide on lead, and calculations based on this possibility might prove of greater use in the future. It was felt, however, that for the present the simplest assumption of an oxide would be the more applicable in the attempt to correlate the results.

With regard to the second assumption (*b*), the roughness ratio for a polished copper specimen has been measured by Rhodin[13] using a gas adsorption technique. He concluded that the bulk of the increase in surface area was produced by the very fine scratches (50–100 Å deep). The figure given by him for the roughness ratio is 2·7. Measurements of a Talysurf recording proved that the increase in surface area due to scratch-brushing was about 10%. The ratio used, i.e. 3, was arrived at by combining these two figures.



(*a*) Ridges in line, coated with different coloured Plasticine
(*b*) Ridged Plasticine coated with different colour, pressed against metal plate
(*c*) Glue-coated Plasticine ridges pressed together

Fig. 3—Behaviour of ridged Plasticine under pressure

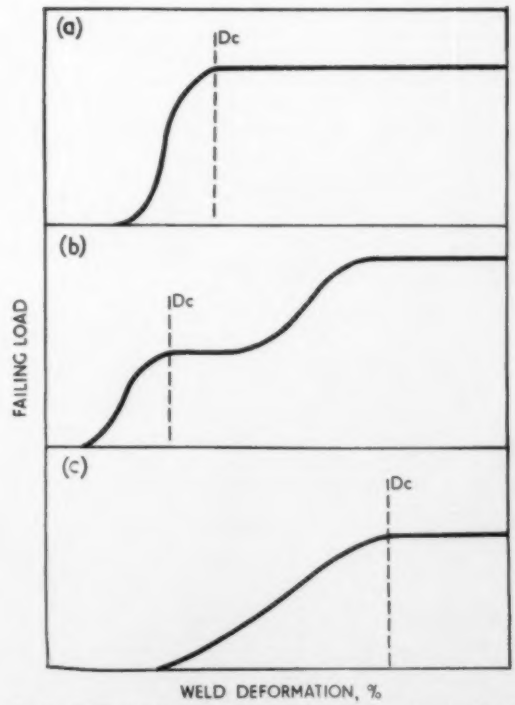


Fig. 2—Critical deformation derived from various types of load/deformation curve

The rise in temperature of a lead specimen (17·3 cm by 2·5 cm wide by 0·01 in. thick) by scratch-brushing, was measured calorimetrically and found to be about 5°C. In this calorimetric experiment the transfer of the specimen from the scratch-brush to the calorimeter was extremely rapid and took not more than 15 s, while in the oxidation experiments a period of about half a minute elapsed before the specimen was transferred to the balance. The rate of fall of temperature of the specimen would be greatest in this initial period and, although no estimate can be made of this rate of fall or of the specimen temperature on entering the balance case, it seems probable that the temperature of the specimen would be little different from that of the atmosphere by this time. All the measurements of increase in weight of specimen were started four minutes after scratch-brushing and one might reasonably expect that by this time the specimen would have cooled to room temperature.

Work-hardening and Softening Curves

The results obtained in this and previous work show that welding begins rather suddenly at a definite deformation. Where this occurs at very low deformations, the cause is believed to be the attainment of metal-to-metal contact over the whole area due to the breakdown of adsorbed gas films on the surface or brittle surface films where they exist. A curve of this type is shown diagrammatically in Fig. 2*a*, and *Dc* indicates the critical deformation.

Where the sudden increase of strength occurs at

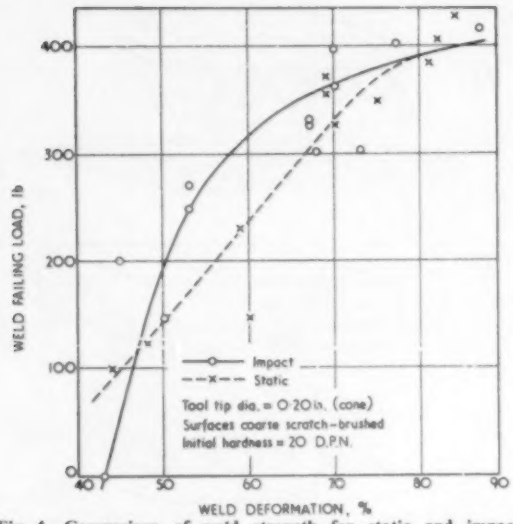


Fig. 4—Comparison of weld strength for static and impact welding of aluminium

higher deformation, it is believed to be coincident with the breakdown of a thicker or softer surface film.

In some cases, particularly with soft metals, a curve of the type shown in Fig. 2*b* is obtained with two periods of fairly rapid increase in strength and two plateaux. In all cases where this type has been found some degree of work-softening or thermal annealing is obtained. The critical deformation for this type is taken as the first rapid increase in strength. The first plateau is believed to be due to work-softening. The second increase is probably a continuation of the first, the work-softening stage being over, and a general increase of weld area is taking place as shown in a previous report.[14]

The third type of strength/deformation curve is shown in Fig. 2*c*. This type indicates that sudden breakdown does not take place and is probably due to a gradual thinning of a comparatively soft film with the area of intimate metallic contact increasing gradually with increasing deformation. The critical deformation in this case is taken as the start of the plateau.

EXPERIMENTAL RESULTS

Mode of Deformation and Behaviour of the Surface Film

Experiments were made with Plasticine models which had grooves cut in them to simulate the scratched-brushed surface of a metal. The angle of the grooves was approximately 60°, and the height about ¼ in. In the first series the grooved surfaces were coated with a thin layer of Plasticine of a different colour in order to simulate a film with similar characteristics to those of the metal. When two grooved surfaces were pressed together with the ridges in contact, some thinning of the surface layer took place in the area of the ridges in contact. On the other hand, when the specimens were placed together with the ridges parallel, there was a tendency for ridges to slip into the grooves on the application of pressure.

When a grooved and filmed Plasticine specimen was brought into contact with a metal plate, thinning of the Plasticine film took place on the ridges, with thickening in the hollows (*see* Fig. 3*b*).

An attempt was made to simulate the case of a thin hard film on a soft metal by brushing ordinary joiner's glue on to grooved Plasticine specimens, and allowing it to set in a vacuum desiccator. The result was a hard tough film which was relatively adherent. With the ridges parallel, and two similar specimens in contact, long wide cracks appeared in the film on the lines of contact of the ridges. Finer cracks were found to be present on the sides of the ridges at right-angles to their length. The result in section is shown in Fig. 3*c*. Contact between the Plasticine had definitely occurred in the areas where the ridges had been, and the crumpled glue film was largely confined to the hollows.

When similarly coated specimens were brought into contact with a metal plate the result was similar, in that the film was broken along the ridges and folded along the grooves.

Generally, these experiments support the theory at first put forward, although it must be remembered that as far as the metal is concerned the conclusions would apply to non-work-hardening metals and alloys only.

Effect of Impactive Deformation

Some previous workers have suggested that pressure welding can be more readily carried out under impactive conditions. For example Carl[15] reports an example of a pressure weld made in worked alpha brass by the detonation of an explosive. After welding the material was harder than before. It would be possible, however, for the high rate of deformation to produce sufficient heat to virtually hot-weld the material which would be work-hardened by continued deformation below the recrystallization temperature.

Crook and Hirst[16] found the opposite effect in the case of indium in air at room temperature. They found that the ratio of weld strength under static loading to that under dynamic loading was three to one. They thought that a certain time was required for the metal to penetrate the protective layers of oxide.

The main purpose in this part of the work was to see if high rates of loading would avoid the work-hardening that takes place with the commoner metals and which tends to nullify an initially favourable hardness ratio.

Annealed commercial-purity aluminium was used, and the results of welds made with a falling weight

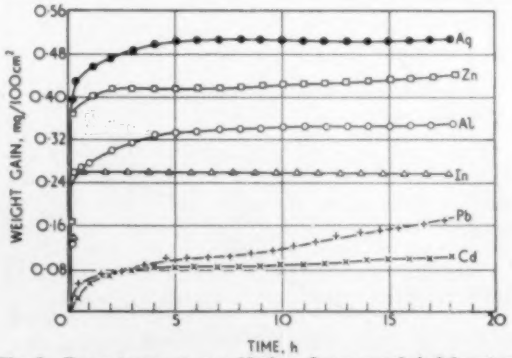


Fig. 5—Room-temperature oxidation of pure metals in laboratory atmosphere: time after coarse scratch-brushing

Table VI

APPARENT FILM THICKNESS ON COARSE SCRATCH-BRUSHED SURFACES AFTER 2 HOURS

Metal	*Thickness, Å*
Aluminium	60
Silver	300
Zinc	130
Lead (PbO)	32
Indium	70
Cadmium	26
Tin (SnO)	174
Copper (Cu_2O)	175

Table VII

COMPARISON OF APPARENT FILM THICKNESS ON COARSE AND FINE SCRATCH-BRUSHED SURFACES

Metal	*Thickness after 120 min, Å*	
	Coarse S.B.	*Fine S.B.*
Aluminium	60	27
Zinc	130	50
Indium	70	23

were compared with those made using the normal rates of loading with a press. A single truncated cone-shaped tool was used against one side, as it was found to stand up better to impact loading.

The results which are plotted in Fig. 4 show that there is virtually no difference in the properties of the welds made by the two methods.

In order to attain higher rates of impact, lead-nosed 0·22-in. dia. rifle bullets were fired at aluminium and copper specimens supported against an anvil. The range was varied from about 20 to 5 ft. With a deformation of 45% on aluminium, there was no welding. On reducing the range to get greater deformation, it was found that the bullet penetrated the specimen and splayed out between it and the anvil.

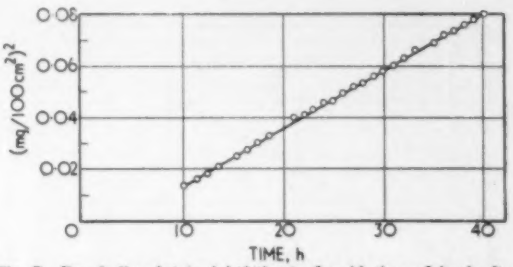


Fig. 7—Parabolic plot (weight² / time) of oxidation of lead after coarse scratch-brushing

In spite of this, mechanical joints were made with a strength of 200–300 lb, due to the drawing of the front half of the specimen through the hole, forming an 'eyelet'.

Similar experiments were repeated on annealed tough-pitch copper. Work-hardening caused an increase of hardness from 46 to 119 D.P.N. with a deformation of 75%, produced by the dropping weight. The rifle bullet produced an increase in hardness from 46 to 125 for approximately the same deformation.

The Thickness and Rate of Growth of Films on Scratch-brushed Surfaces

The results of room-temperature oxidation experiments on indium, aluminium, silver, zinc, cadmium, copper, tin, and lead using a coarse steel wire scratch-brush to clean the surfaces are shown in Figs. 5 and 6. In order that the results might be easily compared the weight gains are plotted as a gain per 100 cm^2.

A linear time scale is used in Fig. 5, while a logarithmic scale is used in Fig. 6, in order to show more clearly the important initial stages of the oxidation process.

The apparent film thicknesses after 120 min estimated from these results are shown in Table VI.

Some of these results were repeated using a fine steel wire scratch-brush to clean the surface of the specimen. The curves which resulted were of exactly

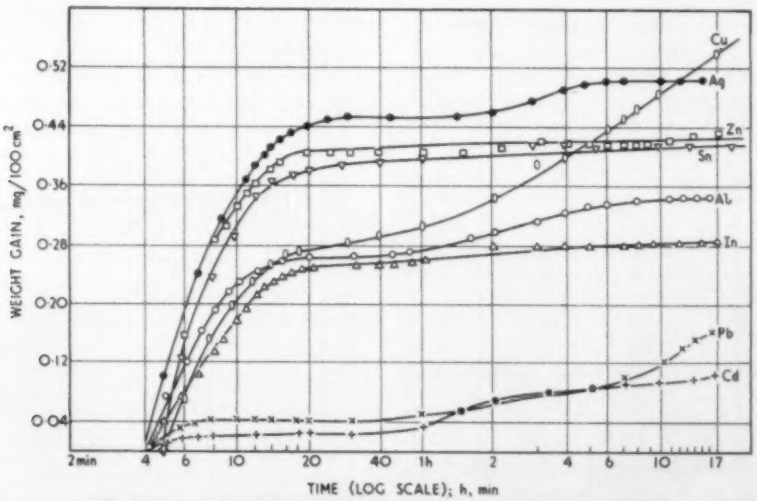


Fig. 6—Logarithmic plot of oxidation of pure metals at room temperature

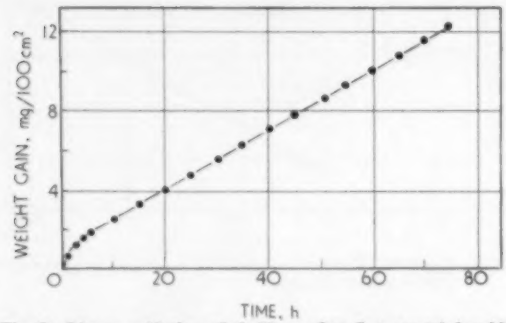


Fig. 8—Linear oxidation of thallium after fine scratch-brushing

the same form and differed only in the magnitude of the weight increase. In every case the increase observed, using the fine-wire scratch-brush, was less than that for the coarse one. These curves are not reported but estimates of film thickness obtained from them are given in Table VII.

In the case of the oxidation of lead at room temperature, the film did not reach a limiting thickness after 40 h. Figure 7, a plot of (weight/area)² against time, gives a straight line showing that the oxidation obeys a parabolic law after 10 h.

The oxidation of thallium cleaned by a fine scratch-brush was also studied and the results of this work are shown in Fig. 8. In this case the oxidation appears to be linear after the initial period of about 5 h. The film formed on this specimen was very thick and could be removed from the specimen. Initially it was a very pale yellow but during the course of the experiment the colour gradually changed to a very dark brown. Analysis carried out on a small amount of this scale showed the presence of a carbonate radical which probably indicates the presence of a carbonate as well as an oxide film on thallium at room temperature.

The result of the oxidation of fine scratch-brushed lithium is given in Fig. 9 which confirms that the rate of oxidation of lithium in air is linear. The linear

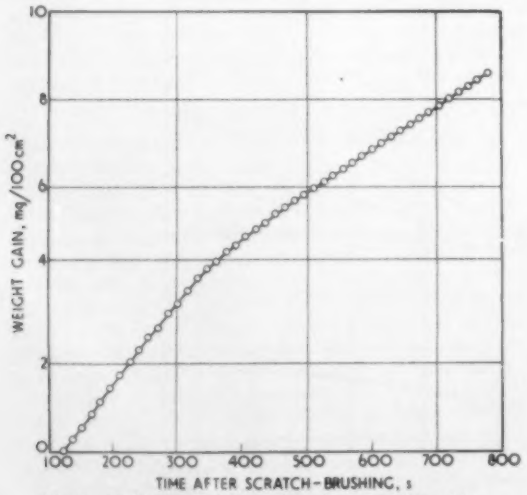


Fig. 9—Oxidation of lithium after fine scratch-brushing

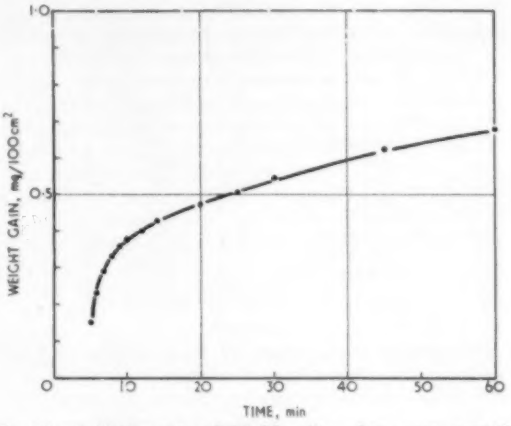


Fig. 10—Oxidation rate of Cd–Mg alloy after coarse scratch-brushing

oxidation rate at short times is greater than the rate at longer times, i.e. after about 5 min.

The only alloy, the oxidation characteristics of which were investigated, was the Cd–5% Mg alloy, which tarnished visibly, forming a dark grey film. The results are given in Fig. 10, and show a roughly parabolic curve during the first 60 min. On plotting the square of the weight gain against time, this resolves into two straight lines intersecting at 10 min, showing that the mode of oxidation is more complex. However, it is clear that the film formed is protective in normal atmospheres. The film attains a thickness of about 170 Å after 1 h, assuming it to be magnesia.

With the exception of thallium and lithium, all the metals investigated formed protective films. However, there is a great difference in the estimated thickness of the films formed. Cadmium and lead form extremely thin films of the order of 30 Å after 2 h. It can be expected therefore that welding within a few seconds after scratch-brushing would be accomplished extremely readily, since the film thickness would be thin enough to bring the metal surfaces into the range of the interatomic forces.

In the case of silver, Tronstad and Hoverstad[17]

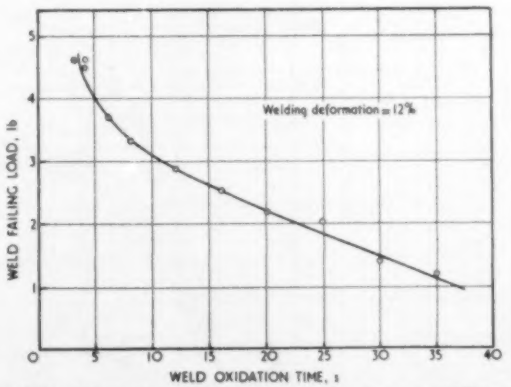


Fig. 11—Effect of oxidation time on the pressure welding of lithium

estimated a thickness of only 10 Å in pure dry air; for this reason the comparatively great thickness obtained in unpurified air might be ascribed to the formation of a sulphide.

The results confirm the formation of an oxide film on indium, the existence of which has been doubted.[1]

The Effect of Oxide/Metal Hardness Ratio on the Welding of Non-work-hardening Metals

Lithium—In the first experiments on pressure welding lithium, the scratch-brushed specimens were pressed together between the fingers as soon as possible after scratch-brushing and then placed between the welding tools. The time between scratch-brushing and the completion of the weld was less than 10 s.

The results of the tensile tests showed considerable scatter which was mainly attributed to variation in time between brushing and welding on a material which was undergoing rapid oxidation.

Therefore, tests were made to determine the effect of variation of the time between scratch-brushing and welding on the weld failing load, using a constant weld deformation of 12%. The strip thickness varied between 0·045 and 0·050 in. The constant weld deformation was produced by applying a weight of 11 lb for a period of 15 s to the press. The total load, which includes the upper tool and holder, was 14·5 lb. The results are given in Fig. 11 which shows clearly the reason for much of the scatter in the previous results. It seems that, after the first few seconds, the variation in weld strength with time between scratch-brushing and welding is a linear one. This linear relationship was to be expected from the oxidation rate, and shows the importance of using an exactly constant scratch-brushing to welding time in experiments to determine the critical deformation of lithium. The variation of weld strength with weld deformation was determined using a constant scratch-brushing to welding time of 10 s. The results are given in Fig. 12, which shows that the critical welding deformation of lithium at room temperature is 10%.

It is interesting to compare Fig. 11 and Fig. 12. According to Fig. 11, the failing load of a weld of 12% deformation after a scratch-brushing to welding time of 10 s is about 3·25 lb. According to Fig. 12, the failing load of a similar weld is about 4·5 lb. Figures 11 and 12 were each determined in one day, but not the same day. The only explanation that can be offered for this difference is that the humidity of the atmosphere had a considerable effect on the strength of welds in lithium.

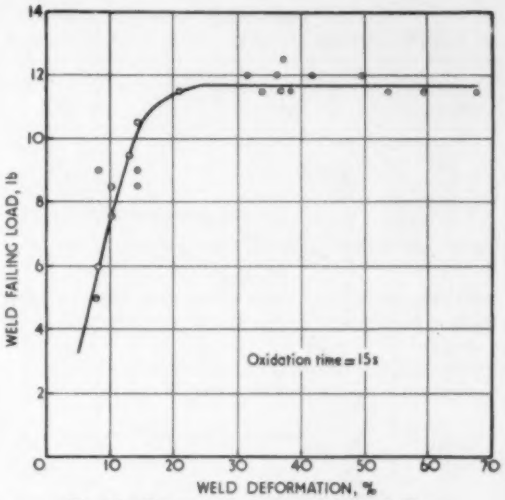


Fig. 13—Strength of pressure welds in thallium

Thallium—The de-greased and scratch-brushed specimens of thallium strip 0·05 in. thick were welded 15 s after scratch-brushing. The pressure was applied for about 10 s, and welds made with various deformations. At higher deformations it was necessary to use a little talc powder on the welding tools to prevent the welds sticking to them. The results of the tensile tests are given in Fig. 13. From this graph it may be seen that the critical welding deformation of thallium at room temperature is 20%.

Solid Mercury—A mould was used for forming strips of frozen mercury about 2½ in. × ½ in. × 0·065 in. In order to facilitate the removal of the strip from the mould after freezing, the mould was initially filled with acetone and then the mercury was poured in, displacing the acetone. After freezing in liquid nitrogen and stripping, the solid mercury strips were handled with chilled tools and asbestos gloves.

The procedure for pressure welding solid mercury was as follows. Two strips of solid mercury were withdrawn from the liquid nitrogen and a short time (25–30 s) was allowed to pass before pressing them

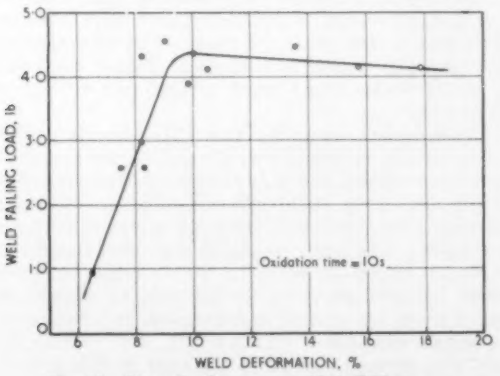


Fig. 12—Strength of pressure welds in lithium

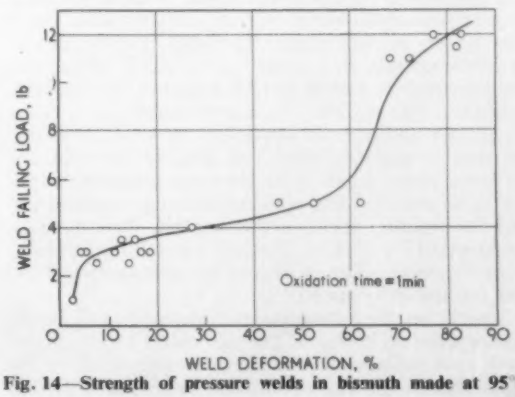


Fig. 14—Strength of pressure welds in bismuth made at 95°C

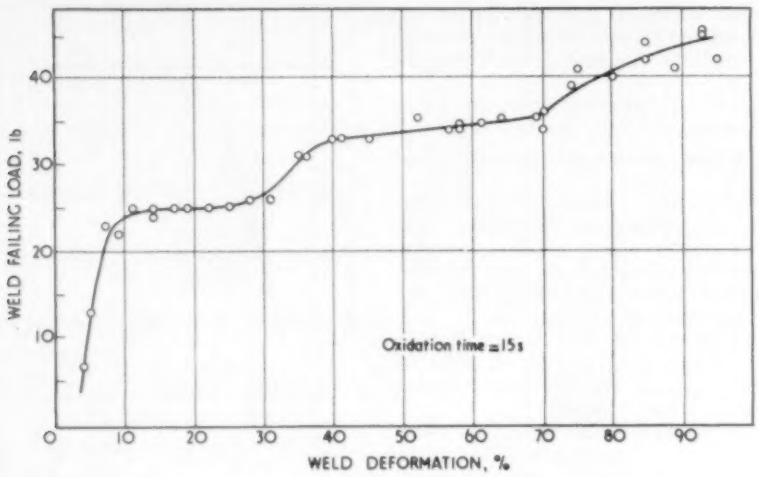


Fig. 15—Strength of pressure welds in lead

together between the tools. This was done in order to allow the solid mercury to become quite soft, in which condition its weldability should be greatest. No preparation of the surfaces to be welded was possible, but in spite of this and the thick film of frozen water vapour which formed on the strips, the critical deformation was found to be very small.

With solid mercury strips of 0·065 in. thickness at an estimated temperature of about —100°C, deformations below 7% failed to produce welds, while deformations above 10% produced good adhesion. In this temperature range, the critical deformation for mercury may be said to be between 7 and 10%.

Bismuth—An attempt was made to pressure weld bismuth at room temperature, but as expected, the metal was not ductile enough to withstand deformations of the order of the critical welding deformation. It was decided, therefore, to investigate the possibility of welding bismuth at slightly elevated temperatures, at which it was thought the metal might be ductile enough to enable welds to be made.

The procedure for pressure welding bismuth at elevated temperatures was as follows. After degreasing and scratch-brushing with the coarse brush, the strips were held together under a slight pressure between the tools, which were at a temperature just a few degrees below the intended welding temperature. A thermocouple was forced between the strips and the temperature raised to that required for welding. When this was reached, the thermocouple was quickly withdrawn and pressure applied to the tools. The time between scratch-brushing and placing between the tools was about 1 min. A further minute elapsed before the tools reached the required welding temperature and the welding pressure was applied. This pressure was applied for 10–15 s. The welds were then removed from the tools, allowed to cool to room temperature, and mechanically tested.

Several welding temperatures were tried in these experiments on bismuth, but the lowest at which bismuth was sufficiently ductile to enable welds to be made was 95°C. The results for welds made at this temperature are shown in Fig. 14. The critical welding deformation for bismuth at 95°C is of the order of 10%.

Lead—Using a scratch-brushing to welding time of 15 s, many welds of various deformations were made and mechanically tested. These results are given in Fig. 15. From this graph it may be seen that the critical welding deformations of lead at room temperature is 10%. This confirms the previous work[1] in which a satisfactory weld was obtained with a deformation of 17%. However, this does not explain the critical welding deformation of 84% given by Sowter.[18] Sowter does not state the interval between scratch-brushing and welding that he used, so assuming that it was longer than 15 s, more welds were made at various deformations, using an interval of one day. During this time the scratch-brushed strips were kept in a desiccator containing anhydrous calcium chloride. The results are given in Fig. 16 and show a decreased weldability.

The variation of weld strength with scratch-brushing to welding time was determined using a constant weld deformation of 28% ±1%. These results are given in Fig. 17.

Zinc and Zinc Alloys—The welding properties of zinc and a number of zinc-base alloys have been investigated to determine the effect of various alloying elements. The respective hardnesses and the condition in which these alloys were welded are shown in Table VIII.

The materials shown in Table VIII were chosen for the following reasons. First, the pure metal for comparative purposes, secondly the zinc–aluminium alloy to improve on the weldability of pure zinc, and finally the zinc–copper and zinc–cadmium alloys to decrease weldability. The last two alloys were investigated in order to determine whether the increase in weldability brought about by the addition of aluminium was due to the general improvement in mechanical properties associated with alloying, e.g. increase in hardness, or to a change in the type of film present upon the metal during the welding operation.

An attempt was made to produce alloys of roughly the same initial hardness, but these alloys work-soften according to the curves shown in Fig. 18. The welding results are shown in Fig. 19 and are summarized in Table IX.

The improved weldability of the Zn–Al alloys is partly due to the harder surface film and partly due to the increased strength of the material, so that welds produced at medium deformation are of relatively high strength.

Cadmium and Cadmium Alloys—Preliminary experiments showed that cadmium welded surprisingly readily 15 s after scratch-brushing, and the critical deformation of 15% which these results gave was widely different from the figure of 84% previously reported by Sowter.[18] The difference between these two figures is similar to that observed in lead and can be explained by the growth in the thickness of the oxide film. Figure 20 shows the results of the experiments on the welding of cadmium as well as the decrease in the hardness of the metal with increasing amounts of deformation, which explains the decreasing weld strength.

Taking these results into account, a second series of welds was produced, and in this the time between scratch-brushing and welding was increased to one hour in order that a thicker film of cadmium oxide might be present during the welding operation. The resulting curve for the pure cadmium (Fig. 22) shows a maximum which agrees well with Sowter's figures for cadmium.

Several cadmium alloys have been produced, including two in which magnesium has been added to improve the weldability. Aluminium could not be used in this instance since it is almost completely insoluble in cadmium and its addition to that metal would simply result in small areas of aluminium in a matrix of cadmium. Magnesium, on the other hand, forms a complete range of solid solutions with cadmium, and although the hardness of magnesium oxide is only about one-third that of alumina (550 D.P.N. for MgO compared with 1800 D.P.N. for Al_2O_3), the improvement it produces in the hardness ratio is quite considerable. Table X shows that pure cadmium has a hardness ratio of 4, while the Cd–1% Mg alloy has one of 22. All three alloys work-soften to some degree, curves for some alloys being given in Fig. 21.

Figure 22 shows the results of welding tests made

Table VIII
CONDITION OF ZINC ALLOYS BEFORE WELDING

Alloy	*Hardness, D.P.N. (5 kg)*	*Heat treatment prior to welding*
Zinc	39	Annealed
Zinc–1% Al	52	Annealed
Zinc–5% Al	55	Annealed
Zinc–1% Cu	48	Annealed
Zinc–2% Cd	60	As rolled

Table IX
RESULTS OF WELDING ZINC AND ZINC ALLOYS

Metal or alloy	*Assumed surface film*	*Hardness*		*Critical deformation, %*
		Metal	*Oxide / Metal*	
Zinc	ZnO	39	6	93
Zn–1% Al	Al_2O_3	52	35	83
Zn–5% Al	Al_2O_3	55	33	83
Zn–1% Cu	ZnO	48	5	93
Zn–2% Cd	ZnO	60	4	93

Table X
HARDNESS RATIOS OF CADMIUM ALLOYS

Alloy	*Hardness of alloy, D.P.N.*	*Assumed oxide on alloy*	*Hardness, Oxide / Metal*	*Treatment prior to welding*
Cadmium	21	CdO	4	Annealed
Cd–1% Mg	25	MgO	22	Hot-rolled
Cd–5% Mg	54	MgO	10	Hot-rolled
Cd–2% Zn	24	CdO	4	Annealed

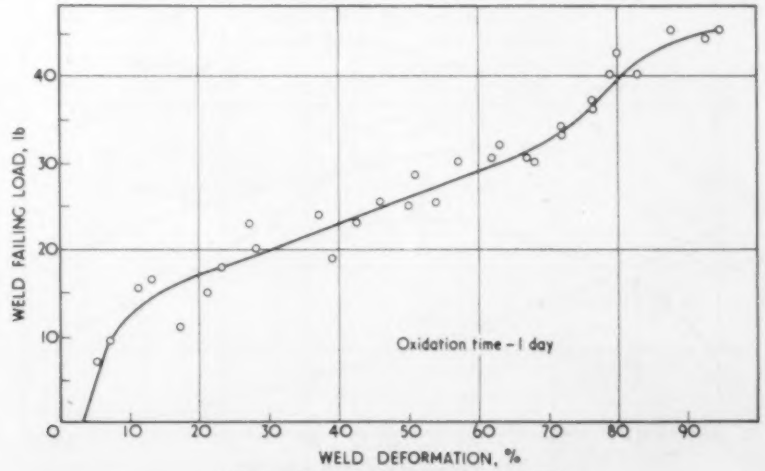


Fig. 16—Strength of pressure welds in lead

Table XI
APPROXIMATE EVALUATION OF CURVES FOR CADMIUM ALLOYS

Alloy	*Hardness, Oxide / Metal*	*Critical deformation, %*
Cadmium	4	40
Cd–2% Zn	4	40
Cd–1% Mg	22	35
Cd–5% Mg	10	35

Table XII
RESULTS OF WELDING SILVER AND SILVER ALLOYS

Alloy	*Hardness of metal, D.P.N.*	*Assumed oxide film*	*Initial hardness, Oxide / Metal*	*Critical deformation, %*
Silver	30	Ag_2O	4·5	80
Ag–5% Al	75	Al_2O_3	24	70
Ag–1% Cu	38	Ag_2O } Cu_2O }	3·5	83

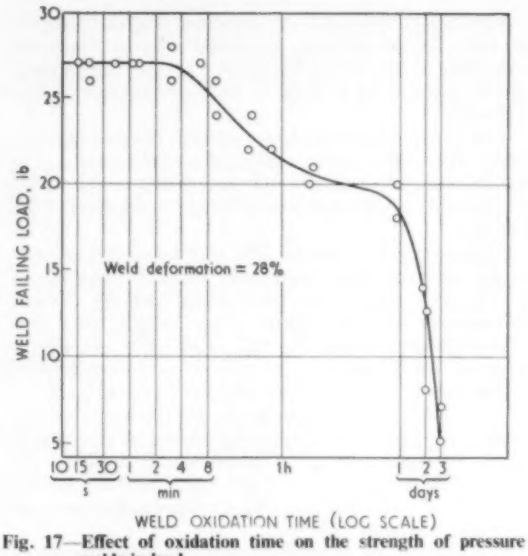


Fig. 17—Effect of oxidation time on the strength of pressure welds in lead

also on cadmium alloys. Welding was carried out 15 s after scratch-brushing since oxide films are believed to form more readily on the alloys. It is seen that the alloys containing magnesium weld rather more readily than the pure cadmium or the Cd–2% Zn alloy. Zinc was added to the latter to raise the hardness to the same value as 1% Mg alloy and still maintain a CdO film, so that a true comparison could be obtained.

Although it is difficult to assess the results in view of the shape of the curves, an approximate evaluation is given in Table XI.

The effect of adding 5% Mg causes a big increase in alloy hardness and therefore reduces the hardness ratio. In spite of this, the improvement caused by the presence of magnesium is maintained, probably because of the large increase in the strength of the material and hence the weld strength. This tends to mask any decrease in the critical deformation caused by the reduced hardness ratio as compared with the 1% Mg alloy.

Tin—According to the oxidation results, tin has a comparatively thick film (about 170 Å after 2 h) which probably consists of SnO or a mixture of SnO and SnO_2. Previous work[1] showed that it welded with a critical deformation of the order of 70%.

However, the results of the present investigation using 99·99% purity Sn, showed that welding, although erratic, could be done with a deformation of the order of 25%, as long as the welds were made within 15 s of scratch-brushing. Results on welds made one hour after scratch-brushing were similar to those previously published and obtained 15 s after

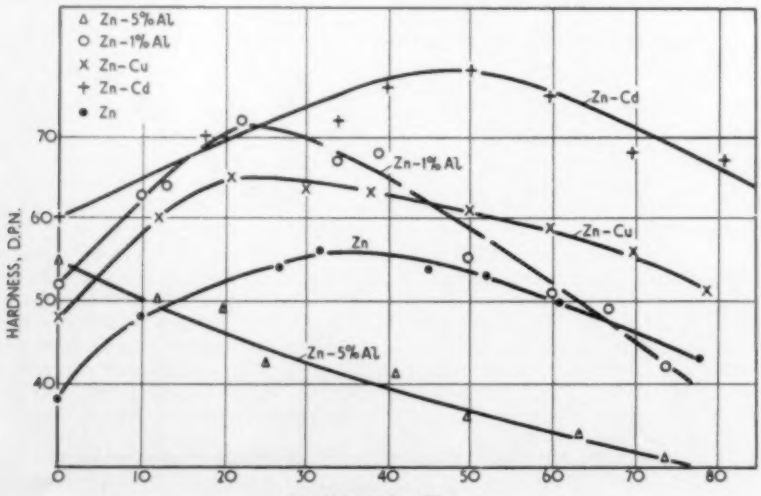


Fig. 18—Work-softening curves for Zn and Zn alloys

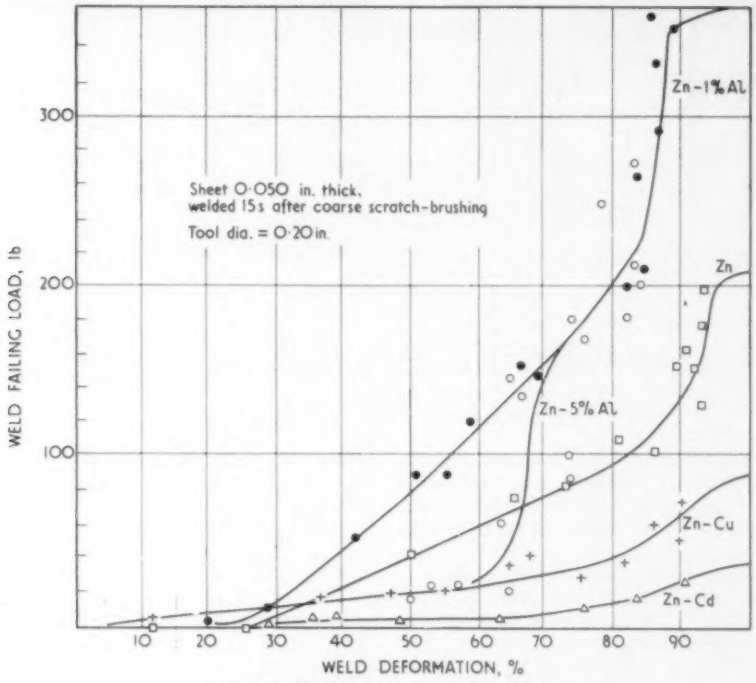


Fig. 19—Welding of zinc and zinc alloys

scratch-brushing, and gave the critical deformation of 70% (*see* Fig. 23).

Work-softening was not found to be very marked on tin, and only amounted to 2 D.P.N. at 88% deformation, after initial work-hardening of the same order at 20% deformation.

Tin was also made the subject of an investigation on the effect of contaminants. While it is generally recognized that grease has a most detrimental effect on welding, it was felt that it would be of interest to obtain quantitative data. Also, a grease film is one of the softest films that can be applied and illustrates the effect that might be obtained with a very soft oxide film. The results are given in Fig. 24 and are compared with those for uncontaminated tin.

Also shown in this figure is the effect of dusting with powdered alumina. It was hoped that the presence of alumina might result in more efficient film breakdown due to the hard nature of the particles, but the presence of the alumina is detrimental although not to the same extent as grease.

The Effect of Oxide/Metal Hardness Ratio on the Welding of Work-hardening Metals

In order to investigate the effect of changing the hardness of the surface film, silver and copper-base alloys were used. The other approach, that of changing the hardness of the parent metal, was also investigated using commercial-purity aluminium and sintered aluminium powder (S.A.P.).

Silver and Silver Alloys—Ag–2% aluminium alloy was made for the purpose of forming a film of Al_2O_3 on silver. However, it proved unsatisfactory, probably due to the failure of the thin Al_2O_3 film to

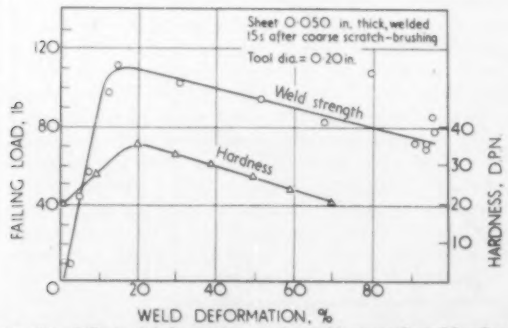


Fig. 20—Effect of deformation on the weld strength and hardness of cadmium

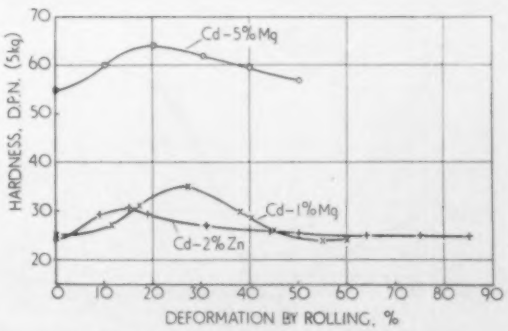


Fig. 21—Work-softening of cadmium alloys

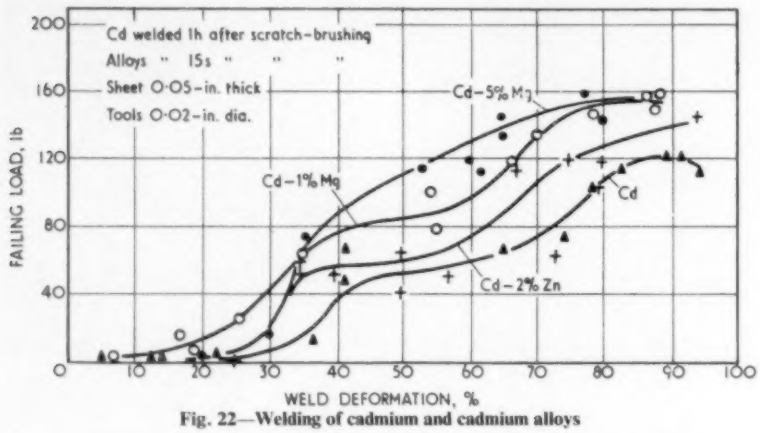


Fig. 22—Welding of cadmium and cadmium alloys

prevent the outward diffusion of silver ions and the consequent formation of a soft film of a silver compound above it. The strength of the welds and the critical deformation were very similar to those of pure silver, shown in Fig. 25. In order to try and ensure the presence of an alumina film, a further alloy containing 5% of aluminium was produced. In this case the alloy is no longer a solid solution but has a duplex structure. The results are also given in Fig. 25 and it appears that the effect of the aluminium addition has been to lower the critical deformation from 80% to 70%. Since the aluminium addition hardens the annealed material from 30 to 75 D.P.N., an Ag–1% copper alloy was made for comparison. This addition had a markedly beneficial effect on the weld strength, although the initial hardness was only raised from 30 to 38 D.P.N. The critical deformation was unchanged, as was expected since the surface film would be of substantially the same hardness as that on silver. The results are summarized in Table XII.

According to the hardness/deformation curve shown in Fig. 26, the surface hardness of the metal can be expected to rise from 30 to 100 D.P.N. in the case of silver, and from 75 to 150 D.P.N. in the case of the Ag–5% Al alloy, thus reducing the hardness ratios to 1·4 and 12 respectively.

The results of welding a Cu–2½% Al alloy are shown in Fig. 27 in comparison with figures obtained with various grades of copper. In order to remove the hard adherent film on the Cu–Al alloy, the material was pickled in 10% H_2SO_4 and linished on an abrasive belt. The results show no improvement when compared with tough-pitch copper, the critical deformations being about 85% in each case.

Work-hardening curves show that at 80% deformation the hardness ratio has been reduced from 29 to 9 in the case of the Cu–Al alloy, compared with a reduction of from 3·5 to 1 in the case of annealed tough-pitch copper. The results are summarized in Table XIII.

Three grades of commercial-purity aluminium sheet were welded: annealed with hardness of 20 D.P.N.; half-hard with hardness of 42 D.P.N.; and fully-hard of hardness 55 D.P.N.

The results are shown in Fig. 28. The curves are very similar, although the harder materials tend to weld

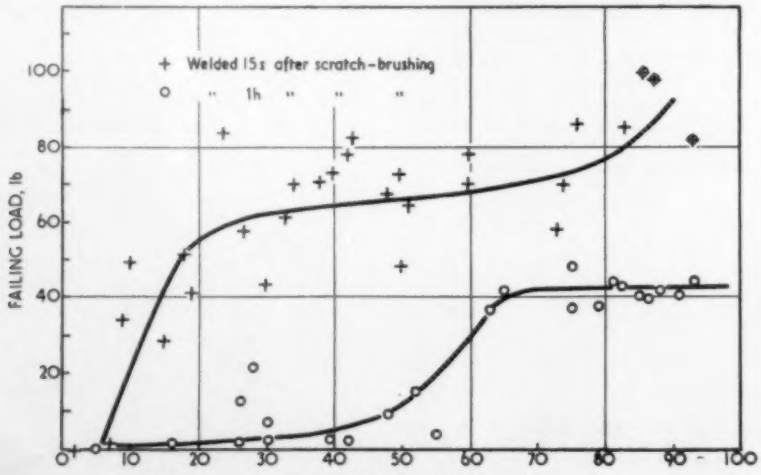


Fig. 23—Strength of pressure welds in tin

Table XIII
RESULTS DEDUCED FROM WORK-HARDENING CURVES

	Metal hardness, D.P.N.		*Surface Film*	*Hardness ratio, Oxide/Metal*		*Critical deformation, %*
	Initial	*80% def.*		*Initial*	*Final*	
Copper (t.-p.)	46	120	Cu_2O	3·5	1	85
Cu–2½% Al	62	210	Al_2O_3	29	9	85

Table XIV
CRITICAL DEFORMATIONS FOR GRADES OF ALUMINIUM

Grade of aluminium	*Hardness, D.P.N.*		*Critical deformation, %*
	Metal	*Oxide / Metal*	
Annealed	20	90	60
Hard	55	33	60
S.A.P.	110	16	60 (approx.)

Table XV
SUMMARY OF RESULTS ON NON-WORK-HARDENING METALS AND ALLOYS

Metal	*Hardness, D.P.N.*		*Critical deformation, %*
	Metal	*Oxide / Metal*	
Li	0·5	220	10
Tl	2·7	50	20
Hg	4·0	1	10
Bi	7·1	63	10
Pb	4·5	5	10
* In	2·3	350	10
Sn	13	29	25
Cd	21	4	15
Cd–2% Zn	24	4	40
Cd–1% Mg	25	22	35 (approx.)
Cd–5% Mg	54	10	35 (approx.)
Zn	39	6	93
Zn–1% Al	52	35	83
Zn–5% Al	55	33	83
Zn–1% Cu	48	5	93
Zn–2% Cd	60	4	93

* Figures derived from previous work[1]

better at lower deformations. The hardness ratios would be 90 for the annealed material and 33 for the fully hard material. However, the hardness/deformation curve (Fig. 27) shows that a ratio of 45 would be reached at 40% deformation in the case of the annealed material before welding had begun, and the effect of annealing would be largely negatived.

The failure to show an appreciable difference could also be explained by the results of tests on the mode of deformation of rough surfaces, from which it would seem that appreciable work-hardening would occur on the asperities before the oxide film would be ruptured.

Sintered aluminium powder has a hardness of 110 D.P.N. due to the presence of finely dispersed oxide. Since no alloying additions are made, the oxide

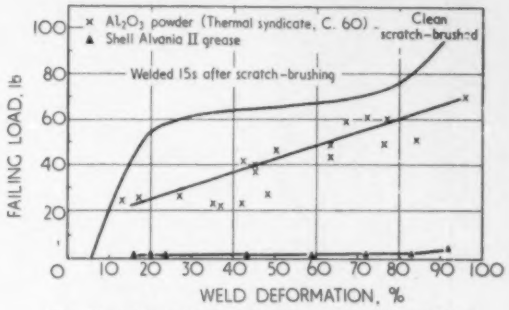

× Al_2O_3 powder (Thermal syndicate, C. 60)
▲ Shell Alvania II grease
Clean scratch-brushed
Welded 15s after scratch-brushing
FAILING LOAD, lb
WELD DEFORMATION, %

Fig. 24—Effect of contaminants on the welding of tin

film can be assumed to be Al_2O_3. In the cold condition it welds surprisingly badly, as shown by the lowest curve of Fig. 28. The reasons for this may be the high elastic recovery due to the high strength of the material, and the fact that the hardness ratio is reduced from 90 to 16 compared with annealed aluminium. However, the critical deformation appears to be of the same order as the other two grades, viz. about 60%.

The results for the three grades are given in Table XIV.

In case the quality of the welds made in S.A.P. was in any way connected with elastic recovery breaking some of the bonds on release of the load, a further set of welds was made in S.A.P. and tested after 'annealing' at 510°C for 24 h. Due to the peculiar properties of this material, this treatment only reduced the hardness a few points. However, the weld strength was increased from a few pounds to 400–500 at 42% deformation. This suggests that, if in fact elastic recovery does result in the breaking of bonds, such bonds are not oxidized and can be reformed by diffusion effects during heat-treatment.

Discussion of Results

The results obtained for non-work-hardening metals are summarized in Table XV. The oxide/metal hardness ratios have been plotted against the critical deformation for welding in Fig. 29, where it is seen that there are many exceptions to the simple theory proposed. It has been shown that the film thicknesses after short times on cadmium and lead are probably so small as to have no effect on weldability. The same

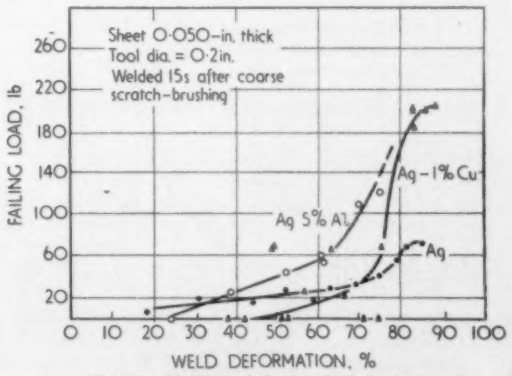


Fig. 25—Welding of silver and silver alloys

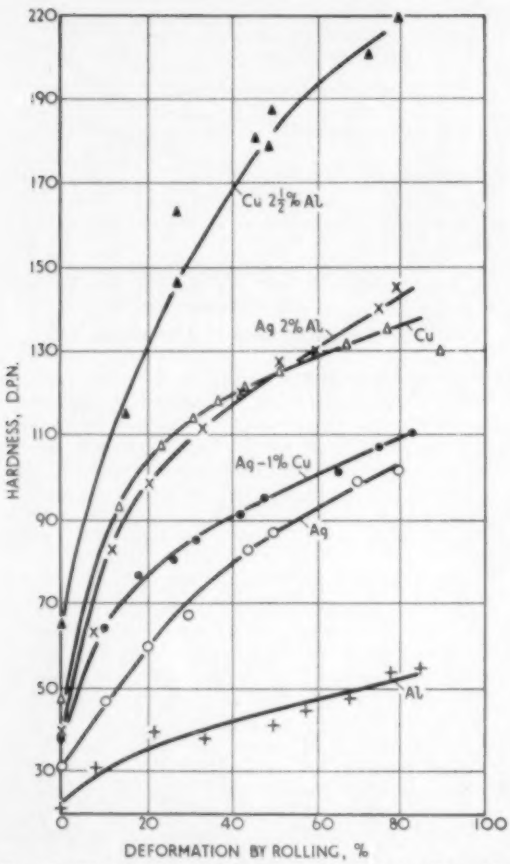


Fig. 26—Work-hardening of copper, silver, their alloys, also commercial-purity aluminium

explanation may apply to mercury, for which Tronstad[17] has found film thicknesses of the order of 15–20 Å at room temperature. Similar considerations could apply to the Cd–Zn alloy, but the Zn–Al alloys remain exceptions. According to Hauffe,[18] the addition of 0·41 % Al to Zn reduces the high-temperature oxidation rate by a factor of 5, but this is explained by the incorporation of trivalent Al ions into the ZnO lattice, which reduces the concentration of interstitial Zn ions. The fact that larger additions such as 1 % and 5 % Al to Zn result in a slight reduction of critical deformation, suggests that an alumina film is forming and is beginning to have a beneficial effect.

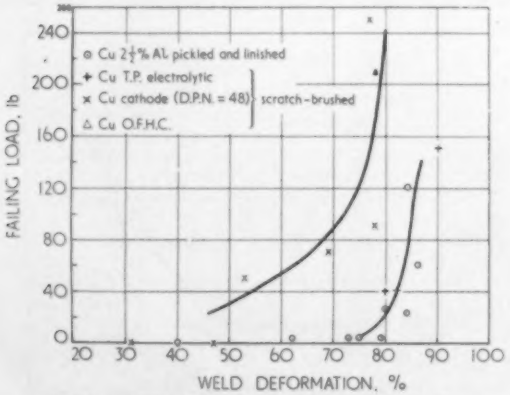


Fig. 27—Welding of copper, and Cu–2½ % Al alloy

Results obtained with work-hardening materials are summarized in Table XVI. Although it is clear that the metals with hard oxide films (with one exception) are welding with rather lower critical deformations, the results show that the oxide-film/metal hardness ratio is having comparatively little effect.

It would appear that deformation of the asperities at the interface in work-hardenable metals is reduced by rapid work-hardening, so that the major part of the deformation takes place in the bulk material supporting the asperities. This has been demonstrated by Bowden, in connection with copper.[20]

The break-up of surface films in pressure welding is probably due to the collapse of the asperities created by scratch-brush leading to the extension of part of the surface. Since thin films, however brittle, can stretch a certain amount without breaking up, a certain degree of deformation of the asperities is essential before metal-to-metal contact is assured. This takes place much earlier in the course of deformation with non-work-hardenable metals than it does in work-hardenable materials.

Plasticine may be compared to a non-work-hardenable metal, and a coloured Plasticine film on Plasticine shows thinning but no breakdown. This may be likened to the unknown case of a film with oxide/metal hardness ratio of unity on a non-work-hardenable metal.

The other extreme, that of a hard film on a non work-hardenable metal, is simulated by a solidified glue film on Plasticine which probably corresponds to

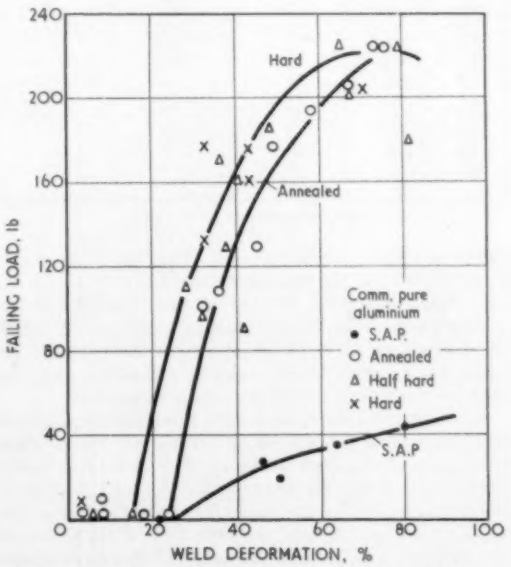


Fig. 28—Effect of hardness on the welding of aluminium

the case of indium. Plasticine/Plasticine contact occurs by cracking of the glue film.

Pugh[21] has shown that thick brittle films on work-hardenable materials, i.e. anodized films on aluminium, break down quite early in the course of deformation. The area of metal-to-metal contact increases steadily, but the weld strength does not, which suggests that elastic recovery is sufficient to break the bonds formed at low deformations.

In the case of the Cu–2½% aluminium alloy no improvement in the critical deformation has occurred, compared with pure copper. It is known that this alloy forms a film at elevated temperatures containing an appreciable amount of copper oxide in the outer layers. It is possible to avoid this by the reduction of the cuprous–cupric oxide film in moist hydrogen at elevated temperatures, but on scratching at room temperature the duplex copper-containing film is reformed. Therefore, if the moist hydrogen treatment were used, it would have to be done after scratch-brushing. Unfortunately, during cooling, a much thicker film of Al_2O_3 would form compared with that formed at room temperature on aluminium.

It is certain that increasing the film thickness whether the film is hard or soft, has a detrimental

Table XVI
SUMMARY OF RESULTS ON WORK-HARDENING MATERIALS

	Hardness, D.P.N.				*Critical deformation, %*
	Metal		*Oxide / Metal*		
	Initial	*Final*	*Initial*	*Final*	
Ag	30	100	4·5	1·4	80
Ag–5% Al	75	—	24	—	70
Ag–1% Cu	38	110	3·5	1·2	83
Cu (t.-p.)	46	120	3·5	1·3	85
Cu–2½% Al	62	210	29	8·5	85
Al (soft)	20	50	90	36	60
Al (hard)	55	55	33	33	60
Al (S.A.P.)	110	110	16	16	60 (approx.)

effect on the weld strength. This has been shown by the author in a previous paper[14] for aluminium, and in this paper for lead.

The fact that a finger-mark or a grease film on aluminium, tin, and many other metals will stop welding completely, illustrates the detrimental effect of a very soft film. What is more, it seems to indicate that the supposition of a soft film on a hard film will nullify the effect of the hard film.

The load/deformation curves for zinc and zinc alloys (*see* Fig. 19) are different in shape from those for the other metals, yet they show the beneficial effect of the aluminium oxide film. The increase in weld strength cannot, as has already been pointed out, be due to increase in weld hardness, since the hardness of the zinc–cadmium alloy was the highest of all. These curves show that film breakdown starts at less than 30% deformation in all cases, but develops most rapidly in the case of the Zn–1% Al alloy.

CONCLUSIONS

The foregoing has shown that the ratio of film

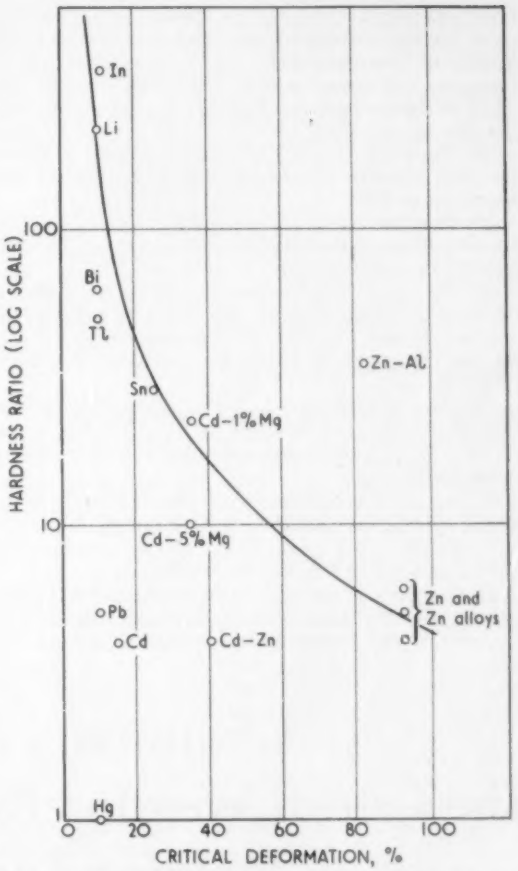


Fig. 29—Effect of hardness ratio on critical deformation of non-work-hardening materials

hardness to metal hardness, in the case of the majority of common metals and alloys, is likely to be an unimportant factor in deciding weldability. However, in certain cases there is a definite relationship between weldability and hardness ratio. In others, oxidation tests have shown the existence of films which are appreciably thinner than the average and which are not of great hindrance to welding, provided that welding is carried out within a few seconds of scratch-brushing.

Some of the more important conclusions are as follows:

(1) In the case of non-work-hardening metals possessing thick films, those such as In and Li which have a relatively high hardness ratio weld more readily than those, such as Zn and Sn, which have a lower hardness ratio.

(2) The surface films on Pb, Cd, and Hg, the latter at −93°C, after 15 s exposure to normal laboratory atmospheres, appear to be extremely thin or may be noncoherent under the influence of pressure. Such metals weld with much lower deformations than their hardness ratios would suggest.

(3) The alloys of Cd, and Zn, like the parent metals, show marked work-softening. The addition of magnesium to cadmium, and aluminium to zinc, shows improved weldability which may be ascribed to the effect of the hard surface film that is produced by the alloying elements.

(4) The addition of 2% Zn results in a reduction in the weld strength and an increase in the critical deformation of Cd.

(5) The addition of 1% Cu and 2% Cd respectively has no effect on the critical deformation of Zn, but reduces the weld strength.

(6) The effect of grease on scratch-brushed surfaces of tin is to inhibit welding. The effect of particles of alumina spread between the specimens is to reduce the weld strength. It would be expected that these effects would apply to all metals.

(7) The addition of 5% Al to silver reduces the critical deformation from 80 to 70%. On the other hand, 1% of copper has no effect on the critical deformation.

(8) A Cu–2½% Al alloy was found to have a weldability similar to that of tough-pitch copper.

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A Summary of the Work of the British Welding Research Association on Welding Low-alloy Steels

By P. H. R. Lane, B.Sc. (Eng.), A.I.M.

SYNOPSIS

The work of the British Welding Research Association on problems in welding low-alloy steels is traced from the original work of the Institute of Welding, dating from 1938 up to the present time. The examination of various steel compositions is described, together with some of the work on the mechanism of heat-affected-zone cracking and the development of the C.T.S. test.

THE SEARCH FOR A HIGH STRENGTH WELDABLE STEEL

The *FM*.8 Committee on Low-alloy Steels of the British Welding Research Association was the successor to the *R*11 sub-committee of the Welding Research Council of the Institute of Welding. From May, 1938, the sub-committee undertook a comprehensive programme of work in order to determine the correct procedure for the successful welding of certain high-tensile steels, and, if possible, to submit recommendations for high-tensile steels with improved weldability.

A summary report of the sub-committee's activities appeared in the *Transactions of the Institute of Welding*.[1] In that paper, weldability tests and mechanical properties were reported for ten low-alloy steels. The weldability tests consisted of Reeve tests (*see* Appendix) and the cracks found in the heat-affected zones were all quite large. Magnetic crack-detecting methods were used, but there was no mention of searching for cracks under the microscope. The steels examined covered a wide range, from a C–Mn steel with 0·18–0·19% C to a 3% Ni steel (*see* Table I). The Dearden and O'Neill carbon equivalent formula[2] (based on hardness) was quoted; the results obtained from the sub-committee's work were in agreement with the conclusions of Dearden and O'Neill. In the conclusions to the paper it was stated that cracking in a restrained fillet weld could be avoided if the maximum hardness was not more than 400 (D.P.N.) or the mean hardness not more than 350 (D.P.N.). Translated into terms of carbon equivalent, this meant that

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Table I

STEELS EXAMINED BY *R*11 SUB-COMMITTEE OF WELDING RESEARCH COUNCIL

Code	Analysis, %									
	C	Si	S	P	Mn	Ni	Cr	Mo	Cu	Zr
*R*11*A*	0·18–0·19	0·087	0·046	0·038	1·54	—	—	—	—	—
*R*11*B*	0·21	0·094	0·038	0·055	1·41	—	—	—	0·52	—
*R*11*C*	0·238	0·060	0·034	0·026	1·40	0·07	—	—	0·04	—
*R*11*D*	0·195	0·11	0·031	0·015	0·68	2·44	—	—	—	—
*R*11*E*	0·31	0·22	0·041	0·040	0·59	3·12	—	—	—	—
*R*11*G*	0·184	0·067	0·036	0·021	0·82	0·03	0·83	—	0·309	—
*R*11*H*	0·08	0·457	0·033	0·149	0·28	—	0·82	—	0·40	—
*R*11*K*	0·11	0·78	0·023	0·012	0·55	—	0·45	—	—	0·10
*R*11*L*	0·065	0·03	0·024	0·010	0·60	1·31	—	0·10	1·13	—
*R*11*N*	0·09	0·135	0·023	0·011	0·38	1·96	—	—	0·95	—
*R*11*P*	0·20	0·170	0·031	0·018	0·70	1·93	—	—	1·05	—

freedom from cracking could be expected with steels of carbon equivalent less than about 0·45%.

When the *FM*.8 committee of the British Welding Research Association was formed (in April, 1945), its terms of reference were as follows:

> To extend present knowledge of the influence of the various alloying elements on weld hardening and the tendency to crack of alloy steels when welded under specific welding conditions with the ultimate object of recommending for commercial development steels of the following classes:
>
> (*a*) Having 0·2% proof stress of 25 tons/in²
>
> (*b*) Having 0·2% proof stress of 30 tons/in²
>
> (*c*) Having 0·2% proof stress greater than 30 tons/in².

The first work carried out for the Committee was the examination of a series of steels with constant carbon and molybdenum content (0·15%C; 0·25% Mo) and 3 levels each of manganese, nickel, and chromium (0·8, 1·2, 1·5% Mn; 0·5, 1·0, 1·5% Ni; 0·25, 0·6, 1·0% Cr). In addition to these 27 steels, four were made with approximately 1% Cu and varying quantities of nickel and chromium, and four more were made with nickel in residual quantities only. Weldability tests were carried out using the modified Reeve test (*see* Appendix).

The steels were all made as 18-lb high-frequency melts and the ingots were forged to give plates just over ½ in. thick, which were normalized and rough surface ground. The first series of test welds were made with 6 and 10 s.w.g. electrodes to B.S. 1719 classification *E*218. Some time later, a second series of tests was carried out using low-hydrogen electrodes of class *E*6- -. The usual mechanical properties were determined on this series of steels in both the normalized and the tempered conditions.

Four further compositions were recommended for wider investigation. Two of these were proposed, on the basis of the tests carried out with rutile-covered electrodes, as showing the best combination of mechanical properties and weldability. These are steels *A* and *B* in Table II; two more were proposed on a similar basis, but related to weldability tests with low-hydrogen electrodes: steels *C* and *D* in Table II.

The two compositions (*A* and *B*) suggested on the basis of the tests with rutile-covered electrodes were made in 2-ton high-frequency induction furnace melts. It was found that the weldability was slightly better, but mechanical properties slightly lower, than had been anticipated from the results of the original series of steels. The 0·5% proof stresses for these steels were (*A*) 31 tons/in² and (*B*) 26 tons/in². In each case the figures relate to normalized ½-in. plate. It was suggested that the alloy content might be altered slightly so as to obtain improved mechanical properties. Accordingly 18-lb high-frequency melts were made in the following series:

(i) 9 melts whose basic composition was similar to steel *A*, but with 3 levels each of Mn and Cr at 0·8, 1·0, and 1·2%

(ii) 4 melts basically to composition of steel *A*, but with carbon contents of 0·12, 0·14, 0·16, and 0·18%

(iii) 4 melts basically similar to the composition of steel *B*, but with carbon contents of 0·14, 0·17, 0·20, and 0·22%.

It was concluded from the tests on these steels that it would not be possible to make a steel similar to composition *B* which would give good weldability with any type of electrode, together with a minimum 0·04% which would be desirable for ease in steelmaking. A composition range based on steel *A* was 0·5% proof stress of 30 tons/in², and at the same time permit a variation of carbon content over a range of

Table II

STEELS SELECTED FOR TESTING IN 2-TON CASTS

Steel	Cast No.	Analysis, %							
		C	Si	S	P	Mn	Ni	Cr	Mo
A	*DB* 8177	0·14	0·18	0·032	0·017	0·89	0·56	0·93	0·22
B	*DB* 8014	0·14	0·30	0·027	0·016	1·14	0·23	0·66	0·24
C	*	0·11–0·15	—	—	—	1·5–1·8	0·6–0·8	0·7–0·9	0·20–0·25
D	—	0·16	0·22	0·039	0·016	1·05	1·13	1·02	0·31

* Steel *C* was not, in fact, made.

Table III
VANADIUM-BEARING STEELS

Steel No.	Analysis, %								
	C	Si	S	P	Mn	Ni	Cr	Mo	V
66	0·13	0·13	—	—	1·05	0·54	1·05	0·26	0·01
67	0·13	0·16	0·033	0·040	1·25	0·57	0·96	0·35	0·01
68	0·13	0·20	0·021	0·039	1·10	0·52	0·94	0·10	0·055
69	0·13	0·20	0·024	0·034	1·09	0·53	0·97	0·29	0·075
70	0·13	0·20	0·028	0·031	1·25	0·55	1·10	0·37	0·064
71	0·125	0·21	0·024	0·029	1·30	0·51	1·09	0·01	0·12
72	0·14	0·17	0·024	0·023	1·18	0·51	1·07	0·13	0·125
73	0·135	0·17	—	—	1·02	0·53	1·03	0·26	0·13
74	0·14	0·18	—	—	1·02	0·54	1·06	0·36	0·125
75	0·14	0·20	0·022	0·035	1·10	0·53	1·07	0·018	0·15
76	0·14	0·15	0·029	0·047	1·05	0·52	1·05	0·10	0·15
77	0·14	0·16	0·026	0·037	1·01	0·51	1·06	0·25	0·19

suggested, but it was implied that the carbon content would be critical to obtain adequate mechanical properties without impairing the weldability. Further tests on steels *A* and *B* were carried out with the test specimens in the hardened and tempered condition. The treatment had no effect on the weldability of the steels, but it improved their tensile properties. Impact properties of steel *B* particularly were high in the hardened and tempered condition. This steel, quenched from 900°C and tempered at 650°C, had a yield point of 34 tons/in² and a transition temperature, based on Charpy tests, of lower than −60°C. The Charpy impact value at +12°C was 160–200 ft-lb.

With a view to finding whether the molybdenum content of steels basically to compositions *A* and *B* could be replaced by vanadium, 6 compositions were selected, 3 each based on compositions *A* and *B*, and 18-lb casts were made. The results of weldability and mechanical tests showed that replacing the whole molybdenum content with a lesser amount of vanadium improved the mechanical properties and gave a high limit of proportionality in the normalized condition without impairing weldability or introducing temper brittleness.

The results of these tests were encouraging enough for a further 12 steels to be made and tested. These contained both molybdenum and vanadium, but had a higher total alloy content than the previous series. They are steels 66 to 77 of Table III. The tests on these were not very satisfactory, and this approach was not pursued further. One of the steels, however, (74) showed a 0·3% proof stress of 40 tons/in² and was crack-free with class *E*614 electrodes at cooling rates (at 300°C) of 5°C to 35°C per second. The absence of cracking at very high cooling rates, obtained with small electrodes, was noted throughout this series.

A 2-ton high-frequency cast was made of one of the compositions derived on the basis of tests on the original series with low-hydrogen electrodes (steel *D*, Table II). The two compositions originally proposed (*C* and *D*) were not very different, but the one which it was decided to examine further allowed the maker slightly wider limits. The mechanical properties of this steel appeared to be quite good, with the exception of the notch impact tests, which gave low results from the as-rolled and the normalized plate.

Good results could be obtained by normalizing followed by tempering at 650°C. In this condition the 0·3% proof stress of ½-in. plate was 32 tons/in² and that of 1-in. plate 39 tons/in². The ultimate strengths were 43 and 55 tons/in² respectively, with room-temperature Izod values of 74–113 ft-lb and 69–97 ft-lb. The weldability was not as good as might be expected, in that cracks were obtained at *TSN* 10 (*see* description of C.T.S. test in Appendix) with 8 s.w.g. electrodes.

Inspection of the compositions given in Table II illustrates one general conclusion from these tests, namely that, to obtain the best combination of mechanical properties and weldability, modest additions of several alloying elements are preferable to large additions of one element only.

Recently, the search for a steel composition giving both good mechanical properties and easy weldability, which was the original aim of the *FM*.8 committee, has been suspended in favour of an investigation of the various factors affecting the occurrence of heat-affected-zone cracks.

MECHANISM OF HEAT-AFFECTED-ZONE CRACKING

Concurrent with the systematic search for a new steel composition, attention was being paid to the fundamental causes of heat-affected-zone cracking. It was early realized that the presence of hydrogen played an important part. It was also appreciated that the rate of cooling of the weld exerted a considerable influence. Attention was also drawn to the fact that there appeared to be a general relationsip between degree of cracking and temperature of transformation.

It was known that the high rate of cooling adjacent to a fillet weld would lead to a transformation temperature rather different from the isothermal one, and accordingly all the original series of Mn–Ni–Cr–Mo steels were examined under continuous cooling conditions, using a rapid-action dilatometer.[3] The transformation temperatures were compared with the tendencies to crack, using rutile-covered electrodes, and the suggestion was made that there was a critical temperature above which transformation should be

completed to avoid cracking. A corresponding comparison was made with the weldability with low-hydrogen electrodes; again there appeared to be a critical temperature for the end of transformation, but, as might be expected, this differed from that found for rutile-covered electrodes. Hopkin later suggested, and demonstrated, that the temperature for the start of transformation, calculated from what is virtually a 'carbon equivalent' formula,[4] showed as good correlation with weldability as the measured temperatures for end of transformation.

Various steels not connected with the systematic investigation were examined, to see if the correlation between transformation temperature and weldability held over a wide range of compositions. It was found that the transformation of a plain 0·5% C steel proceeded differently from the multiple-alloy steels examined earlier, and led to somewhat different critical end of transformation temperatures from those found previously. A 1½% Ni–Cr–Mo steel gave a rather lower critical end of transformation temperature with rutile electrodes than was expected, but it was in reasonable agreement with expectation for low-hydrogen electrodes.

Tensile tests were carried out on small specimens heat-treated to simulate heat-affected zones. There types of test were used: tension-impact, slow tensile, and dead-load rupture tests. Most of the tests were carried out on notched specimens, and were made on a Mn–Mo steel in three conditions. The first of these was as-rolled to ½-in. plate, the second was heat-treated to simulate a welding thermal cycle, and the third was electrolytically charged with hydrogen and then heat-treated to simulate the welding thermal cycle. It was found that, in the tension impact tests, the toughness increased with increasing cooling rate and it was felt therefore that this test did not give significant data related to heat-affected-zone cracking.

In the slow tensile tests the ultimate strength and reduction in area were both reduced for increasing cooling rate. The order of merit (increasing properties) was: heat-treated without hydrogen; heat-treated with hydrogen; as-received. It was felt that, with the high ultimate strength found, even for the specimens heat-treated with hydrogen, the relatively small decrease in ductility could not provide an explanation for cracking of the heat-affected zone.

In the dead-load rupture tests it was found that the rupture stress (defined as the greatest stress which the specimens would sustain for at least 150 h) decreased considerably with increasing cooling rate. It was in this type of test that the greatest difference was shown between the plain specimens and those charged with hydrogen before heat-treatment. It was also found that the rupture stress for the hydrogen-charged and heat-treated specimens could be less than that of the as-rolled material. It was suggested that, with the reduced ductility shown by the hydrogen-charged specimens, if the rupture stress of the hydrogen-charged and heat-treated specimen was less than that of the parent material, cracks would appear on welding. A proposal was made that the tendency of a steel to suffer from heat-affected-zone cracking could be assessed without any welding test, by carrying out dead-load rupture tests on the as-received material and on hydrogen-charged and heat-treated material. If the second of these was lower than the first, it might be expected that cracking would occur.

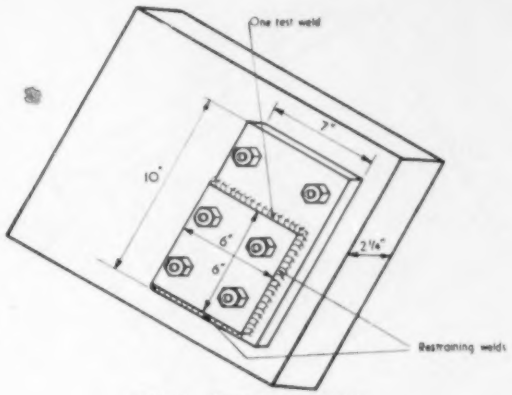

Fig. 1—Reeve test assembly

DEVELOPMENT OF A TEST

From 1948, the *FM*.8 committee work ran concurrently with a contract from the Ministry of Supply. This contract was primarily concerned with determining suitable welding conditions for joints of a military structure to be fabricated from a low-alloy steel. For this purpose the Reeve test was not entirely suitable, since it was desirable that the thermal severity of any test could be adjusted to make it simulate a wide variety of joints. It was therefore necessary to devise a suitable test. Various small tests, based essentially on the Reeve test, were examined and these led to the C.T.S. Test (*see* Appendix).

In the course of the investigations it was found that the gross restraint provided by bolting and welding the top and bottom plates of the Reeve test was not necessary to produce cracking. This should not be taken as implying that restraint plays no part in the development of heat-affected-zone cracking, since the first portion of the test weld laid would itself provide quite a large measure of restraint as soon as it had solidified.

Some empirical observations on cooling rate were made in the earlier stages of the work. A theoretical treatment by Rosenthal[5] indicated that, for any given test, the square root of the rate of cooling at any temperature should be linearly related to the temperature. Experiments confirmed that this was so at all temperatures down to about 100°C.

By plotting curves of temperature against square root of cooling rate for a number of welds in the same steel, some showing cracks and some uncracked, it was found that the two groups could be separated by considering the rate of cooling at 300°C. Accordingly nearly all subsequent work has referred to the rate of cooling at this temperature as being critical. There is probably no theoretical justification for this, but it has been suggested that this temperature is a convenient summation of the high-temperature cooling rate, which would affect the type of transformation, and the cooling rate at lower temperatures where the cracks actually formed.

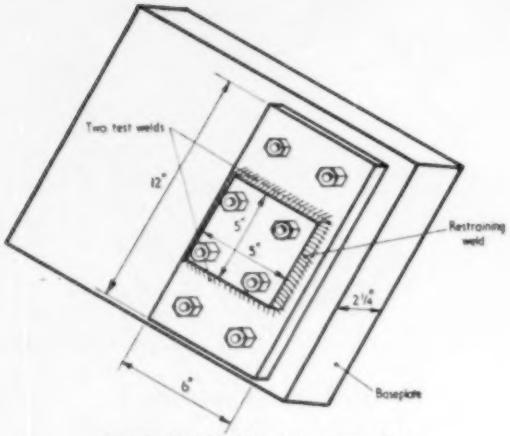

Fig. 2—Modified Reeve test assembly

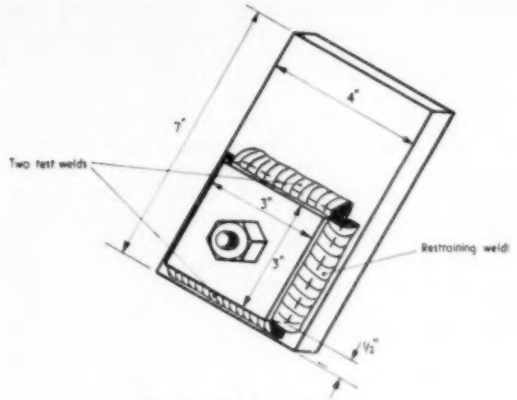

Fig. 3—C.T.S. test assembly

Recently some attempts have been made to obtain information on the reliability of the C.T.S. test. A comparison was arranged on behalf of sub-commission IX*B* of the I.I.W. Two steels were selected, and samples circulated to five laboratories. On one steel the results of the five sets of tests were in good agreement. On the other, two laboratories showed much less cracking than the other three. Subsequent examination showed that the discrepancies could be largely attributed to a failure to observe all the cracks that occurred. It has been found that the examination of specimens must be much more refined than was at first thought necessary.

It should be noted that the whole of the work has been related to fillet welds laid in the downhand position. This restriction was associated mainly with the requirements of the Ministry of Supply contract mentioned earlier, which was concerned with a light assembly which could be positioned for easy welding. However, there is now a growing interest in the use of the low-alloy steels for plated structures and these will almost inevitably require positional welds, which might not be subject to the same conditions as the fillet weld in the C.T.S. test. The use of this test for such work should therefore receive some thought.

APPENDIX

Description of Weldability Tests

The 'Reeve' test provides a high rate of cooling for a fillet weld together with considerable restraint. It consists of two plates of the material under test and of a suitable thickness. The lower plate is 10 in. × 7 in. and the upper plate 6 in. × 6 in. The upper plate is placed on the lower centrally with respect to the width but with its centre line 1½ in. from the centre of length of the lower plate. These two plates are mounted together on a 2¼-in. thick base-plate and rigidly secured by six ⅞-in. bolts. The upper plate is then fixed to the lower with restraining welds around the two sides, and the end nearer the edge of the lower plate. After the assembly has cooled to room temperature and any slack in the bolts taken up, the test weld is laid along the remaining edge of the upper plate (i.e. that nearer the centre of length of the lower plate) (Fig. 1). The weld is left for at least a week and is then cut out; transverse sections are removed and roughly polished and examined with magnetic crack-detecting fluids.

The 'Modified Reeve' test is similar to that described above except that two test welds can be accommodated. The top plate is reduced to 5 in. square and is placed centrally on the bottom plate. The two side welds only are used as restraining welds, and the two end welds are used as test welds (Fig. 2). After removing the welds and sectioning in the same way as for the Reeve test, the weld sections are polished in the normal way for metallographic examination and etched and examined under a microscope at a magnification of 500.

The C.T.S. test consists of a lower plate 7 in. × 4 in. and an upper plate 3 in. square mounted centrally with respect to the width of the lower plate and ½ in. from one end. These two are held together with a $\frac{9}{16}$-in. bolt and fixed with anchor welds along the two sides. Test welds are made at the two ends of the upper plate (Fig. 3).

In this test the whole of the heat sink is supplied by the test plates and these are supported on a heat-insulated jig. There is no heavy base-plate as in the Reeve test. Variations in the heat sink can be made by varying the thickness of the test plates. After welding, the test welds are cut out, sectioned, polished, and examined under a microscope.

A system of 'Thermal Severity Numbers' (T.S.N.) has been developed to relate the test arrangement to any particular practical joint. A T.S.N. of 1 is alloted to the case where heat from the weld can flow through one thickness only of ¼-in. plate (for example a bead on the edge of ¼-in. plate). T.S.N. 2 indicates that there is the equivalent of two paths through ¼-in. plate for the heat to flow away from the weld (a butt in ¼-in. plate or a bead on edge of ½-in. plate). Similarly a fillet weld in a lap joint on ¼-in. plate would have T.S.N. 3 and, on ½-in. plate, T.S.N. 6.

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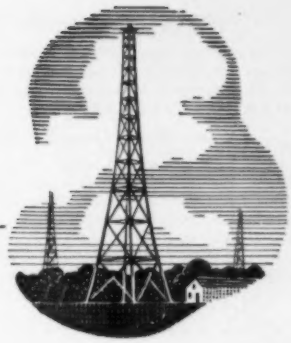
1. *Trans. Inst. Welding*: 1940, vol. 3, pp. 177–202.
2. J. Dearden and H. O'Neill: 1940, vol. 3, pp. 203–214.
3. C. L. M. Cottrell: *J. Iron Steel Inst.*, 1953, vol. 174, pp. 17–24.
4. P. Payson and C. H. Savage: *Trans. Amer. Soc. Met.*, 1944, vol. 33, pp. 261–275.
5. D. Rosenthal: *Welding J.*, 1941, vol. 20, pp. 220s–234s.

Note: Most of the work described in this summary has been published, but in an article of this type it was not thought necessary or desirable to give a large number of references. Some useful references are given in the B.W.R.A. publications "Arc Welding Low-alloy Steels" and "The Weldability of High-Tensile Structural Steels". Some points of detail are discussed in the four papers given below. Any person interested in the work, and wishing to make a more detailed study of the many articles by B.W.R.A. staff and others, is invited to write to the Association.

NEWS
and Announcements



News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE OF WELDING

Donation by T. and I.P.A.

The Tank and Industrial Plant Association has made a donation of £500 to the Institute in response to the appeal for the acquisition and adaptation of the new premises for the purpose of the School of Welding Technology. The Association is also giving to the Institute the unspent balance of its previous contribution to the Guarantee Fund for the Commonwealth Welding Conference. This gift is expected to amount to approximately £100. In announcing the gift, the General Manager of the Association, Mr. A. E. Freestone-Barnes, wrote that at a meeting of his Council "tribute was paid to the excellent work carried out by the Institute of Welding, particularly in the field of specialized technical education".

School Courses in 1958

The courses already announced for January, February, and March, 1958, are now full, except for two or three places in the January course on Resistance Welding.

The prospectus covering the courses from April to September will be available early in January. The following is the outline programme:

April—3-day course on welding for technical college teachers of engineering design subjects
May—Welding in Shipbuilding
June—Inert-Gas Arc Welding
July—Two 3-day courses, overlapping, one on the control of distortion, and one on residual stresses and stress relief
August—No course
September—Design and Construction of Welded Pressure Vessels and Pipework (all places already booked)

It is announced that the course on Inspection and Testing of Welded Work will be repeated between October and December, 1958, but that all places have been reserved. It is possible that this course may be run in duplicate, in view of the great demand.

Appointment of Library Assistant

Miss C. Brayden resigned her appointment as Librarian on account of illness during the late summer, and retired in the middle of November last. The Council of the Institute has placed on record its appreciation of the outstanding services which Miss Brayden has given to the Institute since her appointment as Librarian in 1939, and has offered her its best wishes for her retirement.

The general management of the Library has now been transferred to the Technical Officer, Mr. J. L. Sanders, and the Council has appointed as Library Assistant, Miss W. R. Urwin. Miss Urwin is a qualified Librarian and has been a junior assistant in the King's College, University of Durham, Library since 1953.

Sir William J. Larke Medal

The Council of the Institute, acting on the Report of the examiners, has awarded the Sir William J. Larke Medal for 1957 to Mr. M. Noone and Mr. W. C. Holliday for their paper "Welding of Spheres and Bullets *in situ*", which was published in the October, 1956, issue of the *Journal* and presented at the Autumn Meeting of that year.

The Council also adopted the recommendation of the examiners that honorable mention should be given to the following papers:

Dr. R. A. Cresswell: "Effect of Impurities in Inert-Gas Shielded-Arc Welds" (*Brit. Welding J.*, April, 1957);
Dr. H. G. Geerlings and Mr. W. P. Kerkhof: "Austenitic Welds in 5 %Cr-0·5 % Mo Steel Pipes" (*Brit. Welding J.*, October, 1956);
Mr. A. R. Moss: "Original Researches on Metal Depositing Arcs in Vacuum and Argon" (unpublished paper specially submitted).

The Autumn Meeting—an Apology

Last month's note on the Autumn Meeting mentioned that, in the discussion on the paper "*The Welding of Uranium*" by Gough and Roberts, the authors were "unfortunately unable to answer" some of the questions put to them. What was meant, of course, was that they were prevented from replying by the security regulations; it is regretted that the sentence might have been misconstrued as casting doubt on their scientific competence to reply. In fact, the authors answered the questions put to them as fully as the regulations permitted. The report of the Autumn Meeting, which is being prepared for publication in the *Journal*, will give a full acount of the discussions, with the authors' replies, on all the papers.

Spring Meeting, 1958

The Spring Meeting of 1958 will be held at Harrogate on 8th, 9th, and 10th May. The conference centre will be the Majestic Hotel. As usual, the general theme of the papers will be welding in the local industries, and the following companies have already agreed to receive visits to their works:

British Railways Carriage and Wagon Works, York
W. P. Butterfield Limited
English Electric Company Limited
Kirkstall Forge Engineering Limited
Richard Sutcliffe Limited
The Yorkshire Copper Works Limited

The Leeds and District Branch of the Institute is co-operating in the organization of the meeting.

Dr. H. G. Taylor

Dr. H. G. Taylor has resigned his membership of the Council of the Institute, on ceasing to be qualified as a representative of the Industrial Corporate Members. The Council has accepted Dr. Taylor's resignation with regret.

Extraordinary General Meeting

For a considerable time the Council and its Committees have been engaged in a systematic survey of the constitution and activities of the Institute, and it is expected that they will complete this task at a special meeting early in January. In order to give effect to the Council's recommendations arising out of this survey, it will be necessary to obtain the approval of members for a number of amendments to the Articles of Association and By-laws. It is intended, therefore, to hold an Extraordinary General Meeting for this purpose about the middle of February. Due notice will, of course, be given to Corporate Members.

Commonwealth Welding Conference Proceedings

The Proceedings of the Commonwealth Welding Conference of last June will be published by the Institute early in 1958. The book comprises the sixty papers presented to the Conference, together with a full report of the discussion at the ten technical sessions. It makes a volume of over 400 pages, fully illustrated and covering all the welding processes and their applications, as well as such subjects as education and research. The price of the book will be five guineas (or four guineas to members of the Institute).

CONTRIBUTORS TO THE JOURNAL

H. D. Archbold

J. M. Burke

J. M. Burke was born in 1926 and educated at Ratcliffe College, Leicester. After becoming an Exhibitioner at Gonville and Caius College, Cambridge, he took his Honours Degree in Civil Engineering in 1947. He served in the Royal Engineers for two years, and then joined the staff of F. J. Samuely, Consulting Engineer, in London. In 1952 he was appointed to his present position, Senior Civil Engineer at the Cardiff office of W. S. Atkins and Partners, where he is concerned with the design and construction of welded structures and civil engineering works.

H. D. Archbold was educated at Rutherford Grammar School, Newcastle-upon-Tyne. He served his apprenticeship at Messrs. R. and W. Hawthorn Leslie and Co., Ltd., Hebburn, from 1945–50, during which time he attended the College of Further Education, Newcastle-upon-Tyne, and obtained his Higher National Certificate.

In 1952, he joined the staff of Messrs. Swan, Hunter, and Wigham Richardson Ltd., Wallsend-on-Tyne, and served in the Steel Department of the Drawing Office. Mr. Archbold was promoted to Section Leader in this department and was responsible for the preparation of plans in connection with the construction of the aluminium deckhouses of m.v. *Bergensfjord*.

INTERNATIONAL INSTITUTE OF WELDING

1958 Annual Assembly

The I.I.W. Annual Assembly for 1958 will be held in Vienna from 29th June to 6th July, at the invitation of the Schweisstechnische Zentralanstalt (Welding Research Institute) and the Österreichische Gesellschaft für Schweisstechnik.

The theme of the Assembly will be "Welding in the Chemical Industry", and papers will be presented under the following five headings:

1. Influence of the method of welding, of preheating, and of finishing operations on the properties of welded assemblies, in comparison with those of the parent metal.
2. Welding of clad metals, lining.
3. Special problems in the welding of equipment for the chemical industry and for nuclear plants.
4. Design and calculation of welded products working under high pressure and at high temperatures.
5. Typical examples of welded constructions.

The papers on these subjects will as usual be discussed at the Public Session, on 30th June. From 1st to 5th July meetings will be held of the various Commissions of the I.I.W.

After the Assembly proper, delegates will be able to participate in one of two tours being organized to a number of leading industrial establishments in Austria; there will also be visits to Austrian beauty spots and other places of interest. The Austrian Organizing Committee is willing to assist any delegates who wish to spend their holidays in Austria to organize their stay, if they contact the Österreichisches Organisationskomittee, I.I.W. Annual Assembly, c/o Schweisstechnische Zentralanstalt, Schumanngasse 31, Wien XVIII, Austria, by 31st January.

A detailed programme of the Assembly will be available from the Secretary of the Institute of Welding after 15th January.

OTHER WELDING SOCIETIES

10th Anniversary of South African Institution

The South African Institution of Welding celebrates its tenth anniversary on 1st March. To mark this occasion, a three-day conference is being held in Johannesburg from 19th to 21st March. The programme includes a number of industrial visits, one of these being to a uranium mine, the presentation of welding papers, and, at the end of the conference, the annual dinner. An exhibition of welding equipment and welded products will also be arranged.

New Zealand Welding Conference

The 1958 Annual Conference of the New Zealand Institute of Welding is being held at Auckland from 4th to 6th March. Details may be obtained from the Conference Organizer, Mr. C. H. Boyd, P.O. Box 65, Otahuhu, Auckland, S.E.7, New Zealand.

NEWS FROM INDUSTRY

Engineering and Metallurgical Aspects of Fatigue

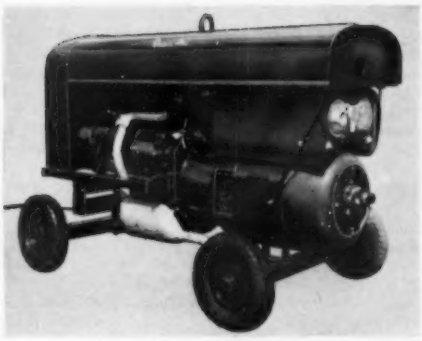
The Metallurgy Department of Battersea College of Technology is holding a course of ten lectures on "Engineering and Metallurgical Aspects of Fatigue", on Tuesday evenings, from 14th January to 18th March, at 7 p.m. The panel of lecturers has been drawn from both research establishments and production works. The fee for the course is £1; all enquiries should be addressed to the Secretary (Fatigue Lectures), Battersea College of Technology, Battersea Park Road, London, S.W.11.

Single-operator Engine-driven Welding Set

A new diesel engine-driven welding set, known as type DEB.400U, has been added to the range of Quasi-Arc Ltd. This is of robust construction, but light and small enough to be easily manoeuvrable (weight without undergear, 19 cwt.). The set has a quick voltage recovery, and is particularly suitable for depositing the cellulose-covered types of electrode (A.W.S.-A.S.T.M. classification E.6010, BS. E.110) frequently used in positional pipe welding.

The set has a particular application for work on remote sites where mains electricity is not available. It gives stable arc conditions when used for pipe welding with 'Celtian' electrodes, and with all other ferrous and non-ferrous types.

The generator is constructed to BS.638: 1954. The maximum current is 400 A, and the maximum continuous hand welding current is 300 A; the open-circuit voltage is 50–95 V. The machine is self-stabilizing, with drooping characteristic.



Field excitation of the welding generator is obtained from a separate belt-driven generator of standard manufacture, as used on many commercial vehicles, so that any necessary replacements are easily obtainable. The excitation generator is mounted on top of the welding generator frame, and is contained within a flexibly-mounted control box, together with the welding generator control gear. The welding generator is flange-coupled to a Ford four-cylinder water-cooled industrial diesel engine.

A fully automatic idling device, controlled by the welding current, reduces the engine speed to idling when welding is not in progress. An adjustable time delay prevents idling during pauses in welding, for instance during electrode changes.

The controls of the welding set are arranged to give the operator the choice of a large number of volt/ampere characteristics. The slope of the characteristic varies with the open-circuit voltage, from fairly flat in the lower range to fairly steep in the upper range, and can easily be varied.

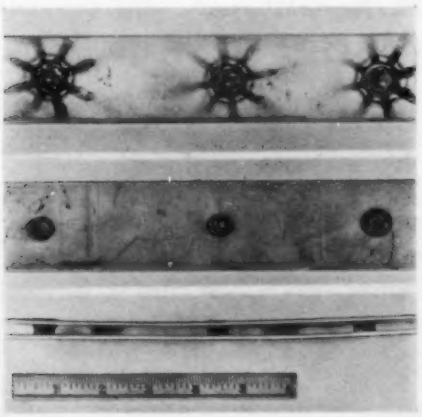
Method of Joining Spaced Metal Sheets

A welding method for joining spaced metal sheets up to $\frac{1}{4}$ in. thick, with spaces or gaps between them up to twice the thickness of the bottom sheet, has been announced by the Linde Department of the Union Carbide International Co. of New York. This 'space welding' process may prove to be an economical substitute for other methods of obtaining spaced-sheet construction, particularly for heat-exchange applications.

The process uses standard 'Sigma' spot-welding equipment, and can be applied to any material that can be welded by the inert-gas-shielded metal-arc process, with the possible exception of aluminium.

Space welding requires little material preparation; it does not require metal-to-metal contact between sheets, specially prepared sheets with prefabricated projections, or holes for plugs.

A delayed wire feed is used with the standard spot-welding equipment and argon shielding. The arc melts a hole through the top sheet and fuses the molten material to the lower sheet. A column of metal is then built up until it fills the hole and fuses with the top sheet. It is possible to obtain a large fused area in the lower plate with no preparation of material to be welded, other than the insertion of removable spacers between the two plates.



Top, bottom, and side views of two sheets of $\frac{1}{16}$-in. carbon steel which have been space-welded. Welding conditions: 280 A, double cycle of 2·2 seconds on, 1·6 seconds off, and 27 volts, using an argon shielding gas flow of 20 ft³ per hour

Tests showed that, in some cases, space-welding requires only single-cycle spot welds, whilst in others, particularly as the spacing increases, double-cycle spot welds were necessary. The nuggets or spacers developed between the sheets are controlled and uniform, indicating that good fusion is obtained on the lower plate. However, the fusion on the lower plate is not necessarily equal to the diameter of the nugget at that point. Though some cold lap may occur, most of it can be eliminated by making an additional spot weld through the lower plate from the opposite side.

Assemblies produced by space welding have a high rigidity as compared with single sheets of equivalent thickness, and they also have a greater bursting strength than those produced by projection or plug welding.

Solenoid Gas-control Valves for Flame Cutting

The 'Hancomatic' dual-carriage oxygen profiling machine shown in the photograph, which is equipped for optical tracing from a drawing, is stated to be the first machine in Britain to be fitted with electrically operated gas-control valves.

On the electrical control panel the switches for the cutting oxygen and preheat flame can be seen in the bottom row. This control panel is duplicated at the other end of the carriage, where the cutting burners are mounted. The valve box containing the solenoid valves adjoins the control panel. Three solenoid valves of large bore ensure ample flows of cutting oxygen, heating oxygen, and fuel gas.

This machine was exhibited at Olympia in September last, and a complete changeover to solenoid gas valves is being undertaken on the 'Hancomatic' production line. These valves are also being fitted to other machines in the Hancock range.

New Indexing Welder

An addition has been announced to the range of indexing welders marketed by Sciaky Electric Welding Machines Ltd.; this is known as the 'PAGM 10', and is suitable for the spot or projection welding, or hot riveting, of small components, such as small electrical parts, electrical contacts, cycle bells, transistors, etc.

The table of the machine can be fitted with any reasonable number of jigs or stations. Driving and indexing of the table is by electric motor, giving, through a gear box, a range of speeds

up to 50 per minute. The air-operated pressure head is fitted with a damper to stimulate shock on the down stroke, this being interlocked with the general mechanism, so that the gear is in the clear position when the table indexes.

The welding current supply and control is made in accordance with the work to be accomplished. Since the work is usually small and therefore the welding sensitive, an ignitron contactor is employed together with electronic timing, usually of a synchronous nature. Various types of unloading mechanism can be used. Normally the machines call for one unskilled operator only to load the pieces into the welding jigs. This machine can also be supplied with magazine loading, in which case one operator can feed a number of machines. This model has an upper rating of approximately 100 kVA.

'Vertivick' Electrodes

Metropolitan-Vickers Electrical Co., Ltd. have recently introduced the 'Vertivick', an all-position electrode for mild-steel welding (B.S.1719 Class E.317), which possesses good qualities for use in the vertical and overhead positions while retaining all the essential features for downhand welding.

These electrodes can be used in the vertical and downhand positions at the current setting recommended for the vertical position, and all the normal positional welding techniques may be employed. As the arc length of the 'Vertivick' electrode is not critical, sound slag-free welds with good mechanical properties can be achieved even by inexperienced welders. These characteristics are valuable where the current control may be remote from the operator, e.g., in shipbuilding, constructional steelwork, and when welding inside tanks or vessels.

The versatile behaviour of this electrode is due to the slag being sufficiently fluid, when welding vertically, to clear quickly from the molten pool, thus avoiding interruptions in the arc, and in the case of downhand welding, to absence of any tendency to flood the arc, even on medium-rust or scaled plate.

Slag can easily be cleaned from the root run of **V**-butt welds; on subsequent runs it is often self-releasing.

The 'Vertivick' electrode has a stable arc which is easily struck, and gives a weld of good appearance, free from spatter and undercut even in the vertical position. It is suitable for use with a.c. or d.c. (either polarity). With a.c. the electrode operates satisfactorily with an open-circuit voltage as low as 45 V.

CORRIGENDUM

In Table I of the paper by Professor Rykalin (December, 1957, issue, p. 544), the plate thickness which can be electro-slag welded using three stationary electrodes should be given as 6–8 in. The value printed is the thickness in millimetres.

DIARY

6th January—INSTITUTE OF WELDING (Sheffield Branch)—Annual Dinner—Royal Victoria Hotel.

6th January—INSTITUTE OF WELDING (South Western Branch)—Welding Forum—Radiant House, Pipe Lane, Bristol, 7.15 p.m.

8th January—INSTITUTE OF WELDING (Manchester Branch)—"*Why Weld Automatically*", by I. C. Fitch—Reynolds Hall, College of Technology, Manchester, 7.15 p.m.

9th January—INSTITUTE OF WELDING (Eastern Counties Branch)—Film Show, including "*Calder Hall Power Station*"—Lecture Hall, Electric House, Ipswich, 7.30 p.m.

9th January—INSTITUTE OF WELDING (East Midlands Branch)—"*Problems of Heavy Casting Repairs*", by D. H. Jones—College of Art, Green Lane, Derby, 7.15 p.m.

9th January—INSTITUTE OF WELDING (North Eastern (Tyneside) Branch)—"*The Use of Forgings and Castings in Welded Fabrication*", by J. Robert—Neville Hall, Newcastle upon Tyne, 7 p.m.

9th January—INSTITUTE OF WELDING (South London Branch)—"*Corrosion and Welding*", by Dr. P. T. Moore—54 Princes Gate, London, S.W.7, 6.30 p.m.

13th January—INSTITUTE OF WELDING (Sheffield Branch)—"*Repairs by the 'Metalock' Process*", by N. Tinwell (Joint Meeting with Rotherham Engineering Society)—Rotherham Technical College, 7.15 p.m.

14th January—INSTITUTE OF WELDING (Liverpool Branch)—"*Welding as a Career for Adventure*", by G. G. Musted—College of Technology, Liverpool, 7.15 p.m.

15th January—INSTITUTE OF WELDING (Medway Section of South London Branch)—Film Show: "*Calder Hall*" and "*Craftsmen Welders*"—Sun Hotel, Chatham, 7.15 for 7.30 p.m.

15th January—INSTITUTE OF WELDING (West of Scotland Branch)—"*The Welding and Use of Notch Ductile Steels*", by J. E. Roberts.

15th January—INSTITUTE OF WELDING (Wolverhampton Branch)—"*Tubes and Hollow Sections*", by G. B. Godfrey—Holly Bush Hotel, Penn Road, Wolverhampton.

15th, 16th, and 17th January—THE INSTITUTE OF PHYSICS—a three-day conference on "*Nuclear Fuel Cycles*"—The Institution of Civil Engineers, London.

16th January—INSTITUTE OF WELDING (Leeds Branch)—"*Radiographic Inspection of Welds*", by E. J. Grimwade—Great Northern Hotel, Leeds, 7.30 p.m.

16th January—INSTITUTE OF WELDING (Southampton Branch)—"*The Building of a Luxury Yacht*", by R. Du Cane—Southampton Technical College, 7 p.m.

17th January—INSTITUTE OF WELDING (Birmingham Branch)—"*Resistance Welding*", by N. H. Jones—Grand Hotel, Colmore Row, Birmingham, 7.30 p.m.

22nd January—INSTITUTE OF WELDING (North Eastern (Teesside) Branch)—"*Welding of Austenitic Steels*", by M. E. Pool Cleveland Scientific and Technical Institution, Middlesbrough, 7.30 p.m.

22nd January—INSTITUTE OF WELDING (North London Branch)—"Sheet Metal Welding"—a discussion led by a Panel of Experts, one each on Gas and Arc Welding, Resistance Welding, and Inert-Gas Welding—54 Princes Gate, London, S.W.7, 7 for 7.30 p.m.

3rd February—INSTITUTE OF WELDING (East Midlands Branch)—"*Brains Trust*"—Victoria Station Hotel, Nottingham.

3rd February—INSTITUTE OF WELDING (Sheffield Branch)—"*Argon-Arc Welding of Non-Ferrous Metals*", by Dr. D. C. Moore—Grand Hotel, Sheffield, 7.15 p.m.

5th February—INSTITUTE OF WELDING (Manchester Branch)—"*Methods of Joining Titanium and its Alloys*", by Dr. D. C. Moore—Reynolds Hall, College of Technology, Manchester, 7.15 p.m.

JOSEPH LUCAS LIMITED

ENGINEERS OR METALLURGISTS FOR GROUP WELDING LABORATORY

required to assist in the development of advanced welding processes for application to the Group's road transport, aircraft, and gas turbine products.

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The positions are permanent and pensionable. Apply in writing stating age, qualifications and experience, to the Personnel Manager, Joseph Lucas (Electrical) Limited, Great King Street, Birmingham 19, quoting reference PM/D/177.

Current
WELDING LITERATURE

Book Reviews
Additions to the Institute Library
Trade Publications

CONTENTS OF PERIODICALS RECEIVED

THIS SECTION is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the *Bibliographical Bulletin of Welding and Allied Processes*, published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.

Brown Boveri Review (Switzerland), 1957, vol. 44, June–July

New Developments in Welding Converters, H. Kocher. (244–247.)

Multi-Operator D.C. Welding Equipment, E. Larcher. (247–251.)

Petrol-Electric Welding Sets, G. Schlüsselburg. (251–259.)

The Problems of Arc Welding Heavy Steel Objects, A. Lüthy and A. Schmid. (260–270.)

The Twin-Wire Automatic Arc Welder and its Applications, A. Smarcan. (271–275.)

Automatic Resurfacing of Steel-Mill Rolls by Welding, A. Smarcan. (276–285.)

The Function of Fluxes in Automatic Arc Welding, A. L. Saboz and C. G. Telschow. (286–290.)

Heat Treatment of Welded Joints, K. Frauenfelder. (290–294.)

Fixtures for Use with Resistance Welding Machines, E. Gut. (295–299.)

Journal of the Japan Welding Society, 1957, vol. 26, September

Fatigue Limit of Narrow Steel Zones and Plates with Welded Joints. (542–547.)

Weldability of Higher-Strength Structural Steels with Tensile Strengths of 60–70 kg/mm², H. Kihara. (547–553.)

Characteristics of the Iron Arc, M. Ozawa, T. Morita, and K. Omura. (554–558.)

Thermal Time Constant of Resistance Spot Welding, K. Ando and T. Nakamura. (558–563.)

Mechanical Properties of Weld Metal, Pt. 1. T. Matsuhara. (563–573.)

CO_2-Sekiguchi's Filler Wire Arc Welding Process, Pt. 4. H. Sekiguchi and I. Masumoto. (573–578.)

Continuous Cooling Transformation Diagrams of the High-Tensile Steel "Wel-ten 55" and Properties of the Heat-Affected Zone by Welding, Pt. 2. H. Sekiguchi and M. Inagaki. (579–585.)

Behaviour of Over-Strained Metals, Pt. 6. S. Morita and S. Goda. (585–591.)

Shrinkage Distortion in Welded Joints, Pt. 7. M. Watanabe and others. (591–596.)

Investigations on the Efficiency of a Welded Strap, M. Otani, S. Ota, and R. Hino. (596–601.)

Lastechniek (Holland), 1957, vol. 23, October

Special issue for "Lastu-57" welding exhibition at Utrecht, giving list of exhibitors, etc.

Articles of welding of pipes, on the following aspects:

Fabrication of pipes and preparation

Pipes as a constructional element

Welded connections in pipes, and related techniques

Examination of welded pipe connections.

Lastechniek (Holland), 1957, vol. 23, November

Enclosed Welding of Rails, J. F. Deenik (273–274) and G. Zoethout. (274–277.)

Acetylene Bottles, H. 't Hart. (278–280.)

Rivista Italiana della Saldatura (Italy), 1957, vol. 9, July–August

Inert-Gas-Shielded Consumable-Electrode Welding of Aluminium, G. Foti. (153–162.)

Schweissen und Schneiden (Germany), 1957, vol. 9, November

Oxy-Acetylene Hard Surfacing of Parts Subjected to Wear, with Particular Reference to Lathe Tools, Grix, Siebel, and Fleck. (473–483.)

Weldable Al–Mg Alloys, P. Brenner. (483–492.)

Warping of Cylindrical Structures due to Internal Stresses caused by Welding, F.-W. Bornscheuer. (492–494.)

Schweisstechnik (Austria), 1957, vol. 11, October

Welding in the Construction of Rolling Stock, K. Mesnaritsch. (109–116.)

Maintenance Work on Welded Tubular Pylons of a 220 kV Transmission Line, K. Meyer. (116–119.)

Schweisstechnik (East Germany), 1957, vol. 7, November

Automatic Submerged-Arc Welding in the U.S.S.R., B. E. Paton. (393–397.)

Welding Technology at the Leipzig Technical Exhibition, W. Becker (399–406.)

Equipment for CO_2 Welding, Pt. 2. G. Hebold. (407–410.)

Strength of Welded Fork Joints in High-Pressure Steam Piping, H. Pohl. (411–413.)

Testing for Rust in Submerged-Arc Welding Flux, P. Beyersdorfer and G. Becker. (413–414.)

Welding Journal (U.S.A.), 1957 vol. 36, October

Shielding Gases for Inert-Gas Welding, H. Helmbrecht and G. W. Oyler. (969–979.)

Electrical Requirements for Automation in Arc Welding, R. W. Tuthill and R. D. Mann. (980–985.)

Thermal Analysis of Brazing and Hard-Surfacing Alloys – a Proposed Method, F. M. Miller. (986–991.)

Zinc Soldering of Aluminum, I. B. Robinson. (992–997.)

Stress Relieving of Weldments, E. R. Parker. (433s–440s.)

The Welding of Type 347 Steels, A. Hoerl and T. J. Moore. (442s–448s.)

Mechanism of Microcracking in Mild-Steel Welding, K. Winterton. (449s–456s.)

High-Temperature Brazing of Aluminum Bronze to Inconel, D. Caplan and E. F. Nippes. (457s–464s.)

The Effect of Impact on Beams and Welded Structural Connections, P. J. Brennan and H. A. B. Wiseman. (465s–472s.)

Welding Journal (U.S.A.), 1957, vol. 36, November

A New CO_2 Welding Process (using bare flux-cored electrode), A. F. Chouinard and R. P. Monroe. (1069–1073.)

Butt Welding Austenitic Stainless Steel to Ferritic Steel in Cylindrical Shapes, J. E. Donahue. (1074–1077.)

Bonded Fluxes for Submerged-Arc Welding of Alloy Steels, H. C. Campbell and W. C. Johnson. (1078–1084.)

A New Welder Busway Distribution System, L. E. Fisher and R. W. Dailey. (1085–1096.)

Diffusion Phenomena in Pressure Welding, A. G. Guy and A. L. Eiss. (473s–480s.)

Vacuum-Metallurgical Research gives Industry a Glimpse into the Future, R. C. Bertossa. (483s–489s.)

Crack Initiation and Propagation in the V-Notch Charpy Impact Specimen, C. E. Hartbower. (494s–502s.)

Relation of Charpy Impact Properties to Microstructure of three Ship Steels, W. S. Owen and others. (503s–511s.)

Welding and Metal Fabrication, 1957, vol. 25, December

Heavy Welded Fabrications. (454–460.)

Automatic Flame Profiling of Plate in Shipyard Practice, W. H. Pearse and R. R. Sillifant. (461–468.)

A New Type of Brazing Furnace. (469–471.)

Practical Application of Inert-Gas Metal-Arc Welding to some Aluminium Alloys, E. M. Wilson. (474–481.)

The Reactor Vessel at Berkeley. (482–485.)

Zeitschrift für Schweisstechnik (Switzerland), 1957, vol. 47, November

Jigs and Positioners for Resistance Welding, E. Gut. (268–275).

Flame Bevelling, Pt. 2. J. Pratt. (275–278.)

History of Welding Electrodes, Pt. 2. F. Wörtmann. (279–287.)

Other Journals

A New Automatic Pressure-Butt-Welding Machine. (*Shipbuilder and Marine Engine-Builder*, 1957, vol. 64, Nov., pp. 652–653.)

Welded Tubing Spurs Zirconium Use. (*Steel* (U.S.A.), 1957, vol. 141, Oct. 21, pp. 80–82.)

Testing of Aluminum Hopper Cars, J. F. Whiting. (*Metal Progress* (U.S.A.), 1957, vol. 72, Oct., pp. 125–128.)

CO_2 Arc Welding of Steel, P. C. van der Willigen and L. F. Defize (in English). (*Welding News* (Holland), 1957, No. 83, July–Aug., pp. 2–14.)

Oxidation-Resistant Brazing Alloys. (*Metal Industry*, 1957, vol. 91, Oct. 25, pp. 358, 362.)

Materials Selector (including welding properties of the metals listed). (*Materials in Design Engineering* (U.S.A.), 1957, vol. 46, mid-Sept.)

Electrode Quality Depends on Coating, H. F. Reid, Jr. (*Steel* (U.S.A.), 1957, vol. 141, Sept. 30, pp. 83–84.)

BOOK NOTICE

EARL R. PARKER, "*Brittle Behavior of Engineering Structures*": New York, 1957, John Wiley and Sons; London, Chapman and Hall Ltd., 324 pp. (£2 8*s*.).

Any publication on brittle fracture in the field of engineering construction will find earnest readers today. This book by Professor Parker is a valuable discussion of data on many aspects of the problem. It may be recommended as a handbook for technicians in need of a general introduction; but it is doubtful to what extent the practising engineer or designer will find much direct guidance in overcoming the difficulties with which he is confronted.

The book leans too heavily on American experience to pass muster as a textbook of international calibre, and, despite the scope which the title implies, is concerned almost entirely with sub-atmospheric temperature brittleness in medium-carbon steel. Admittedly, mild steel is still the most important constructional material, but brittleness from either the cleavage cracking or fast fracture standpoint could be troublesome in a variety of alloy steels, non-ferrous metals, and non-metallic materials. Are there no hazards here? If so, the book should have dealt more fully with them or not let its title suggest that it has in fact done so.

The introduction in Chapter I covers ground which should be the stock-in-trade of any brittle fracture study—the T-2 oil tankers, fracture terminology, notch effects, welding stresses, steel composition, and structural design. However, the lay reader would profit from a perusal of Chapters XI and XII (non-ship and ship failures) before embarking on the rest of the book. Chapter I includes a discourse on the 'classical' theory based on triaxial stresses at a notch root, which would have been better put under the "Theories of Fracture" section. The explanation on page 9 of the influence of plate thickness is unconvincing. It is not clear *why* the thickness direction stress component at the notch root is worse for a 1-in. plate than a $\frac{1}{2}$-in. plate. Width/thickness ratio is irrelevant in the quasi-infinite plate of a real structure; hence the triaxiality theory has recourse to root radius to introduce a size factor.

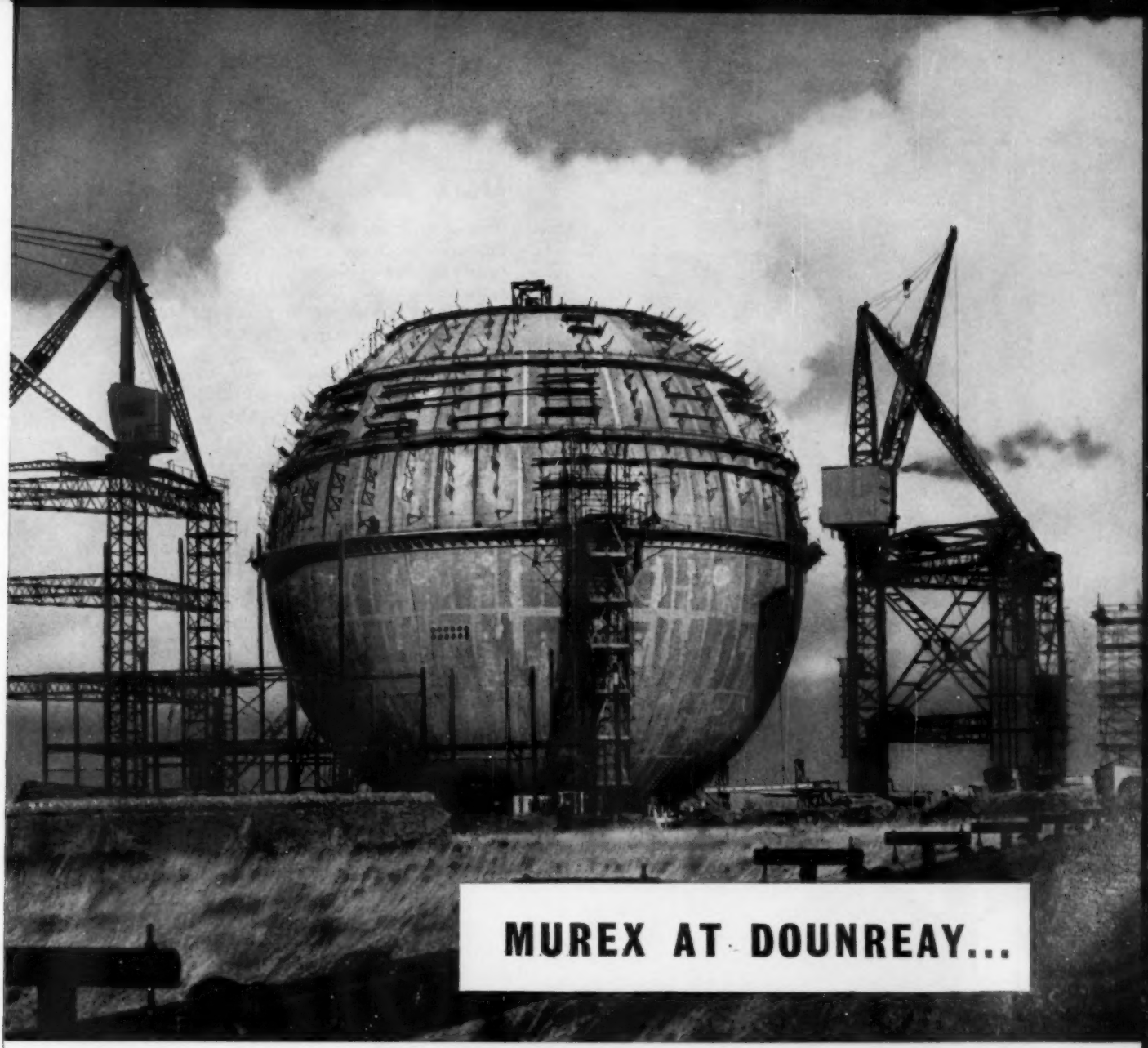
The author works hard with the material on test specimens and produces some remarkably good correlations; in fact, the plots on pp. 154 and 155 are so impressive that any recognized test appears to arrange different steels in more or less the same order. Chapters VII and VIII, on the rôles of chemical composition and welding, are among the best in the book, probably because the background technology involved is well documented and conclusions about the influence of various factors are easier to draw. Surprisingly, no direct reference is made to Bessemer steel.

Residual stresses lead the author to conclude that no unambiguous conclusions can be reached. Nevertheless, it is a pity that important statements on the subject are scattered about the book. Thus, on p. 222, the facts (on low-temperature stress relieving) are said *not* to support the contention that benefit is derived from metallurgical changes rather than absence of residual stresses *per se*, whereas on p. 20 (on high-temperature stress relieving) it states that the greater part of the improvement is due to metallurgical changes.

On faults in fabrication, the importance of weld quality is emphasized. This is vital in as-welded joints. For structures destined to be fully stress-relieved at high temperature, it is feasible that some relaxing of strict quality standards would be permissible, but the point is not discussed.

In writing a book on behalf of a Project Advisory Committee, Professor Parker has clearly been in danger of producing a series of statements diluted to avoid offending too many sensibilities. Happily, such a criticism does not apply to the final chapter, which is an admirable Summary.

G. COATES.



MUREX AT DOUNREAY...

60 MILES OF FORTREX 35 ELECTRODES

Over 300,000 ft. of Murex Fortrex 35 Electrodes were used for welding the above sphere at the Dounreay Atomic Energy Plant. These electrodes were exclusively used for all the manual arc welding on this unique and massive sphere which is 135 ft. in diameter and is made up from nearly 300 plates. The sphere has been built by the Motherwell Bridge and Engineering Co. Ltd., Motherwell, to the most exacting requirements of the U.K. Atomic Energy Authority. For such applications only the best electrodes can be used. Murex electrodes are at your service.

Other contractors at Dounreay using Murex electrodes include Alex. Findlay Ltd., Matthew Hall & Co., Ltd., Head Wrightson & Co. Ltd., John Thompson Ltd., Thos. W. Ward Ltd., and Whatlings Ltd.

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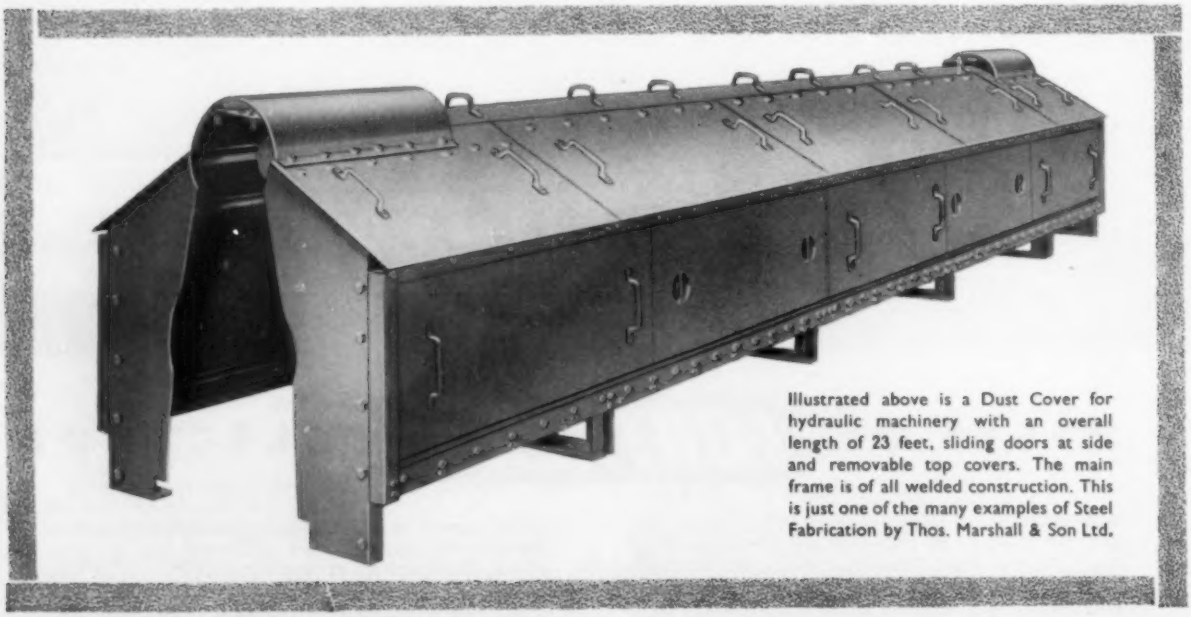

Illustrated above is a Dust Cover for hydraulic machinery with an overall length of 23 feet, sliding doors at side and removable top covers. The main frame is of all welded construction. This is just one of the many examples of Steel Fabrication by Thos. Marshall & Son Ltd.

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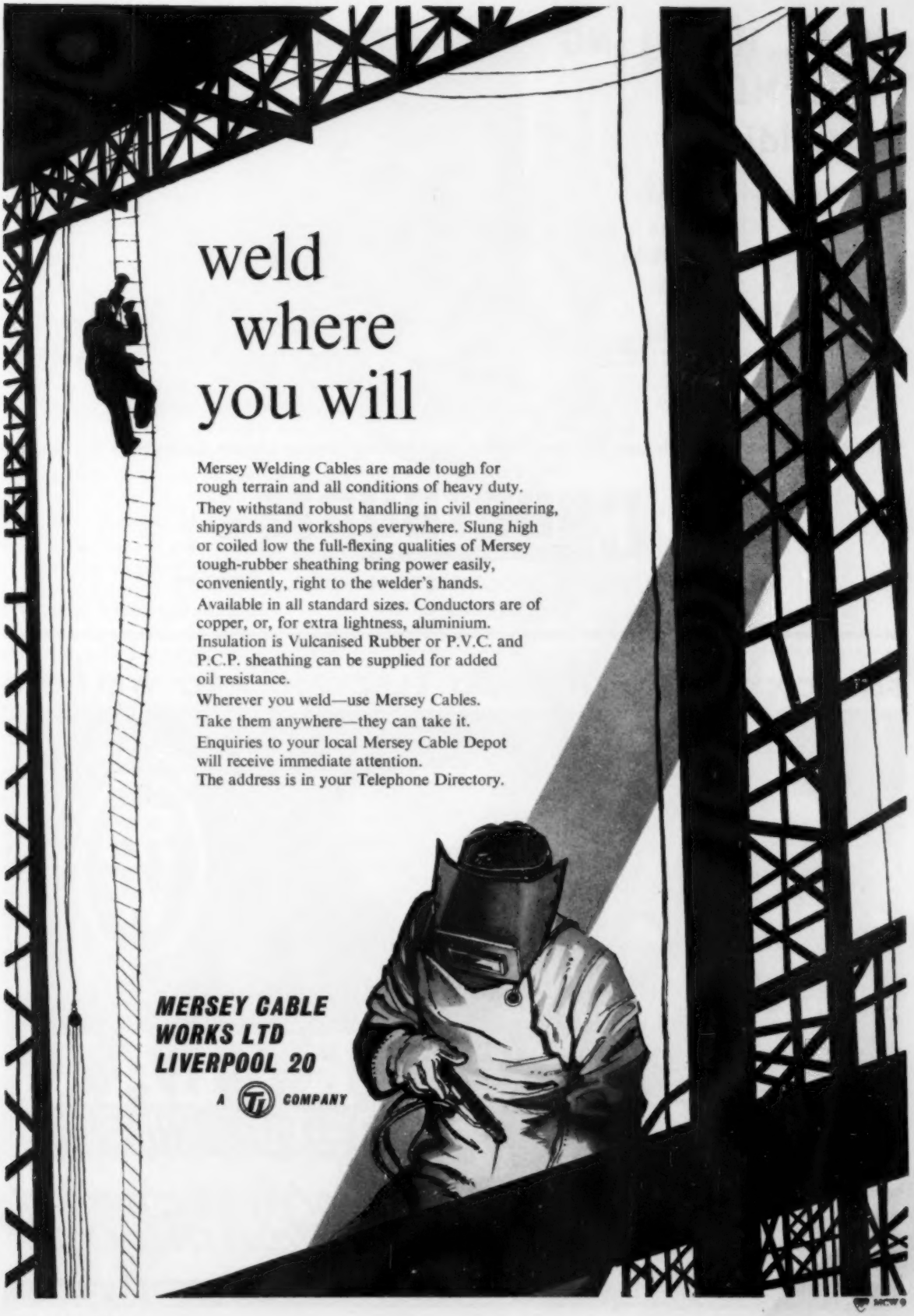
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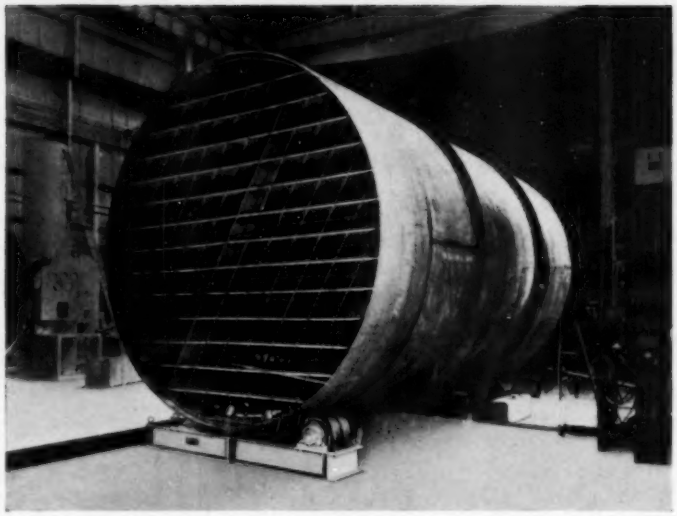

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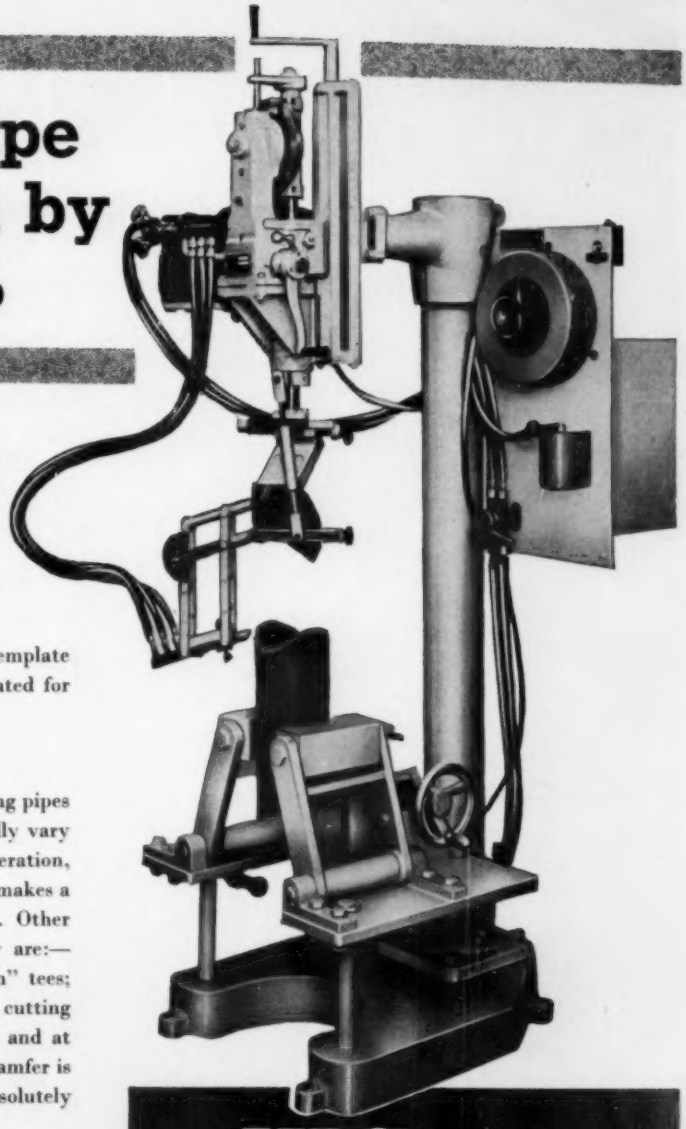

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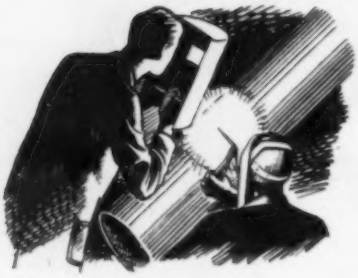

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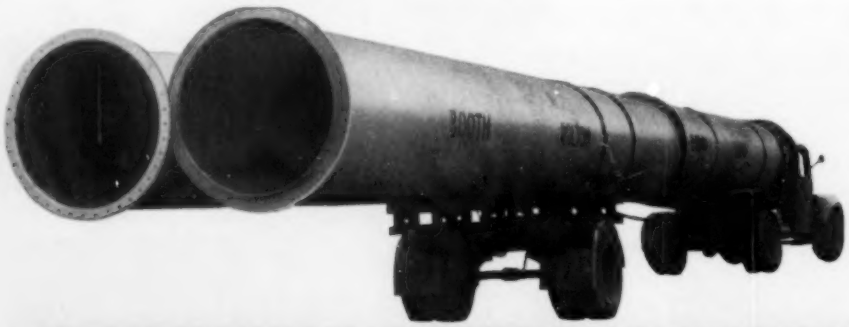
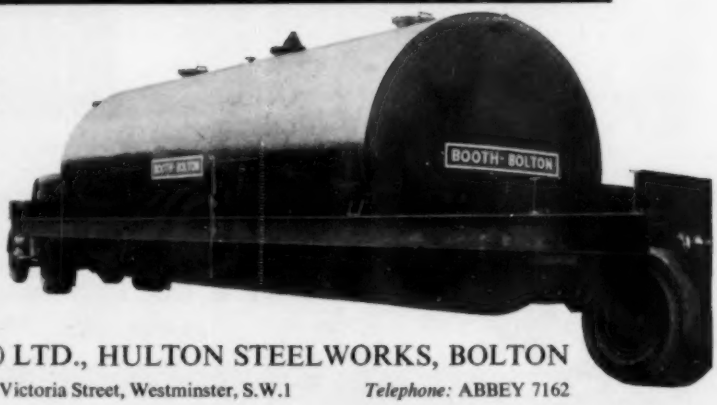


Sections of Mild Steel Chimneys 4′ 0″ dia.

BOOTH WELDING*

Mild Steel Triple Compartment Tank 30′ 0″ long × 10′ 6″ dia. 15,600 gallons capacity. Note: limited headroom at site necessitated this low loading arrangement



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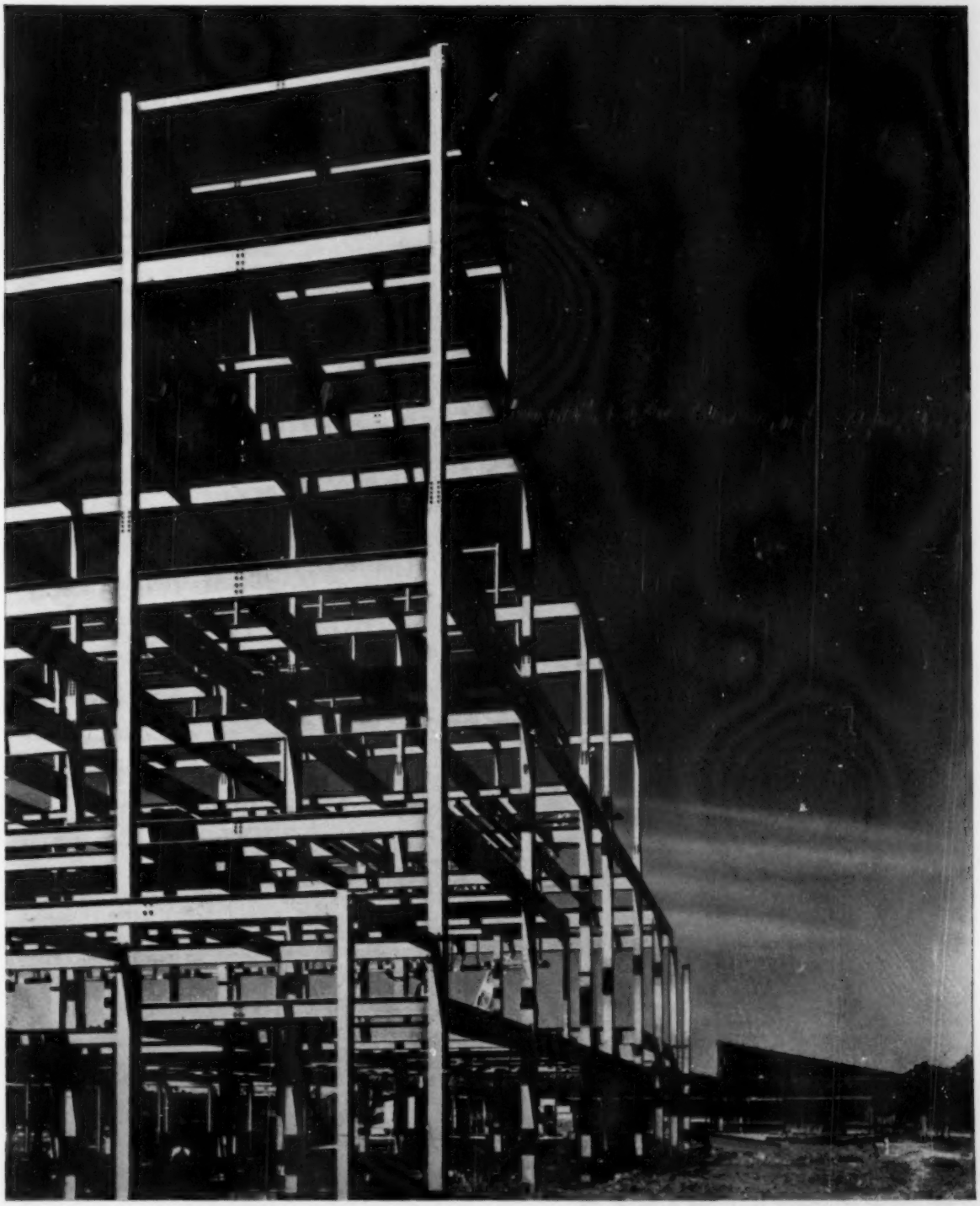

Part of the steel framed structure supplied to British Nylon Spinners (Australia) Pty. Ltd. for their new factory at Melbourne.

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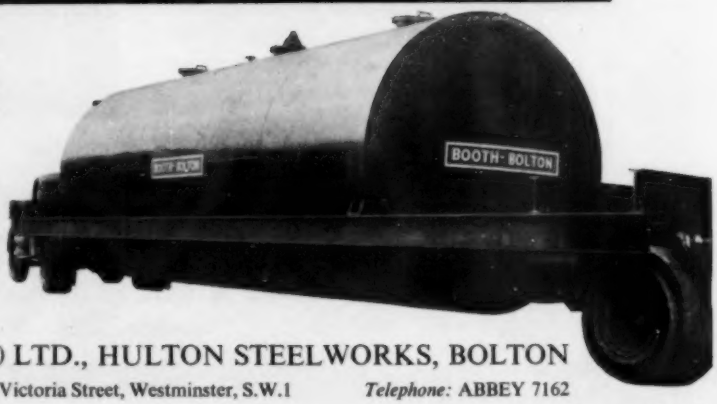

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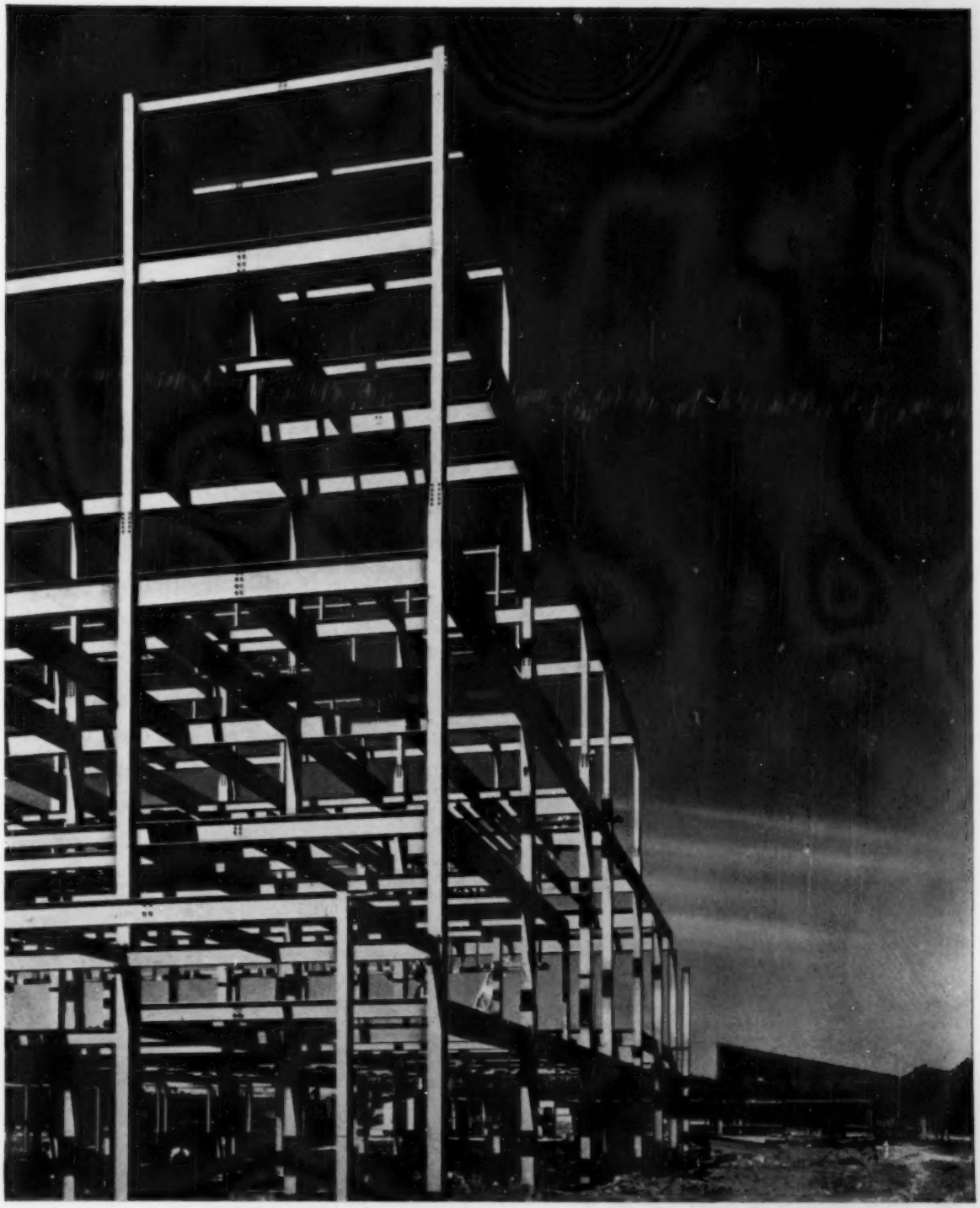

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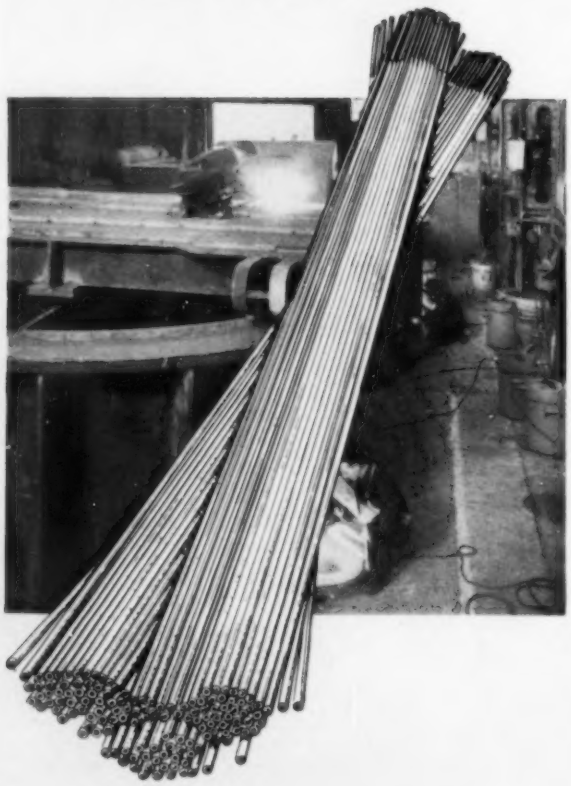

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